NOAA TECHNICAL MEMORANDUM
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OPERATIONAL APPLICATIONS OF THE REAL-TIME NATIONAL LIGHTNING DETECTION NETWORK DATA AT THE NWSO TUCSON, AZ

Darren McCollum, David Bright, Jim Meyer and John Glueck
National Weather Service Office
Tucson, Arizona

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Operational Applications of the Real-Time National Lightning Detection Network Data at the NWSO Tucson

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ABSTRACT

Real-time data from the National Lightning Detection Network (NLDN) were used in the operational setting at the NWSO at Tucson, Arizona since February of 1995. A summary of the utility of real-time lightning data at Tucson is presented. The operational staff found lightning data to be useful for concise briefings of convective events already occurring. Consensus was that lightning data filled in the gaps that are inherent in the time and space resolutions of the WSR-88D at Tucson and GOES satellite imagery. Lightning data were used for backup power decisions, improved public safety information, to mitigate the effects of radar beam blockage, analyze storm structure, monitor low topped convection, observe thunderstorms in Mexico and summarize national lightning activity. Analysis of lightning data from the monsoon season in 1995 clearly showed the monsoon season progression of convective systems across southeast Arizona as well as the cloud-to-ground lightning hot spots for the season. Lightning data are compactly stored and allow a quick assessment of the overall convective season, convective outbreaks and the ability to identify individual storm systems of interest for study. Also, it is proposed that seasonal averages of lightning data can be used in conjunction with sparse rainfall data across southeast Arizona to improve rainfall estimates.

1. INTRODUCTION

Since February of 1995, real-time National Lightning Detection Network (NLDN) data have been used in the operational setting at the NEXRAD Weather Service Office (NWSO) in Tucson, Arizona. Access to real-time cloud-to-ground (CG) lightning data was made through a special arrangement with Global Atmospherics Inc. (GAI) of Tucson, Arizona which is responsible for managing the NLDN.

The NLDN has provided lightning data covering the continental United States since 1989. Using observations gathered from 105 sensors distributed throughout the continental United States, the NLDN provides both real-time and archived lightning data to commercial and government users. The basic system configuration of the NLDN is shown in Fig. 1. Ground-based sensors detect the electromagnetic signal produced by a lightning discharge (1) and transmit salient information to the Network Control Center (NCC) in Tucson, Arizona via a two-way satellite system (2-3). This "raw" data from the remote sensors is processed at the NCC (4) to provide the time, location and peak current of each detected discharge. This processed information is sent back to the communications network for satellite broadcast dissemination (5) to real-time users (6). All this takes place within 30-40 seconds of a lightning flash (Cummins et al. 1995). The NLDN provides the most reliable and technologically advanced lightning detection data commercially available on a real-time national basis.

In the sections that follow, various aspects of the NLDN real-time lightning data are summarized and discussed. Section 2 presents a brief background of lightning detection systems. The history of the NLDN is summarized in Section 3. In Section 4 the lightning detection efficiency and location accuracy of the NLDN are presented. The remaining sections describe how real-time CG lightning data have been used at the NWSO at Tucson to supplement WSR-88D observations/operations, improve mesoscale forecasting and enhance public safety. The general uses of NLDN data as expressed by forecasters at the NWSO Tucson are summarized in Section 5. Section 6 discusses the specific ways in which NLDN data have been applied in the operational setting. In Section 7, the potential uses of lightning data on station for local climatological studies and research are presented.

2. LIGHTNING DETECTION

Lightning detection systems are designed to detect the electromagnetic signal that is produced when a lightning flash occurs. Incoming electromagnetic signals are continuously analyzed by receivers to determine if a CG lightning flash has occurred (Cummins et al. 1995; Holle and Lopez 1993). Computer algorithms are used to discriminate between CG and non-CG lightning flashes. The NLDN is designed to retain CG flashes only (Cummins et al. 1992; Maier 1991).

When a CG lightning flash is identified, its location must be determined. The NLDN has used Direction-Finding (DF), Time-Of-Arrival (TOA) and a combination of DF/TOA technologies at various times in its history.

Direction-Finding (DF) methods incorporate cross-loop antennas to detect the electromagnetic signal emitted by a lightning flash. Each antenna consists of two vertical loops perpendicular to each other oriented north-south and east-west. The horizontal azimuth vector of a lightning flash relative to an individual antenna can be computed from the current induced in the cross-loop antenna. The location of a CG lightning flash is then approximated by triangulating the computed azimuth between two or more DF antennas (Fig. 2a and b). The company Lightning Location and Protection, Inc. (LLP), now part of GAI of Tucson, Arizona, is the primary producer of DF systems. Before 1994, the NLDN used DF systems only. For a more in-depth discussion of DF systems refer to Holle and Lopez (1993).

Time-of-arrival (TOA) methods detect differences in the arrival time of the electromagnetic signal produced by a lightning flash. Each antenna detects the signal produced by a lightning flash and assigns a time-of-arrival to the peak amplitude of that signal. The antenna receiver must be synchronized to a dependable time standard such as the Global Positioning System (GPS). The difference in time-of-arrival between each antenna pair is computed and defines a branch of a hyperbola anywhere along which a CG flash could be located (Fig. 3a). A minimum of three antennas, placed within 200-400 km of one another, are required to determine the location of a lightning flash. For two pairs of antenna the point at which hyperbola branches intersect (i.e., the solution for both hyperbolas) is the location at which the CG flash occurred (Fig. 3b). The company Atmospheric Research Systems, Inc. (ARSI) now also of GAI, is the primary manufacturer of TOA systems. The lightning detection network called Lightning Position and Tracking System (LPATS) uses TOA technology. For further reading on TOA systems, refer to Holle and Lopez (1993).

More recently, GAI engineered a "hybrid" lightning detection system called Improved Performance from Combined Technology (IMPACT) which uses a combination of both DF and TOA methods. For a given CG lightning flash, each IMPACT sensor provides a horizontal azimuth vector pointing toward the CG flash (DF) and the time it took a signal to propagate from its origin to the sensor which is used to define a range circle (TOA). For a group of sensors, the solution that causes all horizontal azimuth vectors and range circles to intersect (achieved through iterative computations) is the approximate location of the flash (Fig. 4). The IMPACT system produces redundant lightning location information and allows a more precise determination of lightning location than DF or TOA systems alone (Cummins et al. 1995).

3. HISTORY

The NLDN began as a research program at the State University of New York at Albany (SUNYA). The initial network was comprised of 10 lightning sensors along the east coast of the United States (Orville et al., 1983). The electric utility industry realized the potential value of CG lightning data and funded an expansion of the "SUNYA Network" through the Electric Power Research Institute (EPRI) of Palo Alto, California. EPRI is a cooperative research branch of the electric utility industry which commissions research projects around the United States to improve the efficiency of electric power companies. By 1990, the "SUNYA Network" was combined with lightning detection networks operated by the Bureau of Land Management (BLM) and the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma (Orville 1990) and encompassed the contiguous United States.

During 1991, due to increasing demand for lightning detection data, LLP, and EPRI formed Geomet Data Services (GDS) which was made responsible for the management, operation and maintenance of the NLDN. GDS oversaw the installation of 34 new DF systems in the western United States during the summer of 1992 which eliminated the reliance on the lightning sensors operated by the BLM.

In 1993, GDS was making plans for further upgrades and experimented with the IMPACT sensors in parts of the NLDN, demonstrating significant improvement in lightning location accuracies (Cummins et al., 1995). The NLDN was officially upgraded in 1994 by combining the 34 IMPACT sensors and 65 LPATS sensors. Figure 5 shows the outlay of the combined networks. Today GDS, LLP, and ARSI form GAI, owned by the Sankosha Corporation of Japan.

4. NLDN LIGHTNING DETECTION EFFICIENCY AND ACCURACY

Lightning detection efficiency is the percentage of actual CG lightning flashes that are detected. Various experiments have been undertaken using multiple video cameras to estimate the detection efficiency of the NLDN. This research supported a NLDN flash detection efficiency of approximately 70 to 80 percent (Fig. 6a) within the contiguous United States (Cummins et al. 1995). No lightning detection system is capable of detecting 100 percent of lightning flashes and the detection efficiency of the NLDN can vary significantly between storms. This is especially true for flashes that occur at the periphery of detection networks, when a flash is not surrounded by antennas and/or when a portion of the network is not functioning properly. However, the experience at Tucson suggests that, in general, the detection efficiency of the NLDN is more than adequate for meteorological purposes.

The location accuracy of the NLDN is a measure of the confidence that a detected CG lightning flash occurred within a specific distance of the plotted position. The results of rocket triggered lightning experiments and multi-camera observations of thunderstorms have been used to estimate the location accuracy of the NLDN (Cummins et al., 1995). The results of these experiments suggest that 50 percent of detected lightning flashes are located within 0.5 km of a plotted position (Fig. 6b). Once again network performance and strikes near the edge of networks experience more uncertainty but real-time usage in Tucson suggests that the location accuracies stated by GAI are reliable.

5. GENERAL USAGE OF NLDN REAL-TIME LIGHTNING DATA AT TUCSON

A. SURVEILLANCE

i. Rapid Assessment of Thunderstorm Events

The operational staff at Tucson found the real-time NLDN data to be an indispensable tool for the quick assessment of the thunderstorm environment across southeast Arizona. Several loops of the real-time lightning data allowed a forecaster to identify where thunderstorms were forming, dissipating, moving, the location of updraft/downdraft regions and the probable degree of mesoscale organization (Holle et al. ,1994; Watson et al. ,1991; Lopez et al., 1990; Mosher 1989; Lopez et al., 1989). It provided a separate time and space scale on which to visualize the overall storm evolution. Such a rapid assessment is not possible with the WSR-88D Doppler weather radar at Tucson (KEMX) since the presence of thunderstorms is necessarily inferred and requires more in-depth analysis of the data. During the 1995 summer monsoon season in Arizona the lightning data facilitated concise briefing of operational staff coming on shift or called in during severe thunderstorm events and was usually the first choice for a quick storm summary in such situations.

ii. Supplement to Areal Coverage of KEMX

The NLDN lightning data were a critical supplement to the areal coverage of KEMX in several ways. Thunderstorms that were located beyond the range limits of KEMX (e.g., thunderstorms located in Mexico) were easily monitored and usually first identified by lightning data. The real-time lightning data allowed forecasters to track thunderstorms as they moved into and out of the range coverage of KEMX. Low topped thunderstorms below the radar beam that occurred during the winter were easily identified. Lightning data allowed continuous surveillance when thunderstorms moved through or developed within the cone of silence (a 20 to 30 km radius surrounding the radar where the beam angle is too low to fully detect storms) of KEMX. Finally, data voids caused by gaps in KEMX coverage due to beam blockage were filled in with lightning data during convective events. The NLDN data provided an extra dimension of observation and provided a means to fill the apparent gaps in KEMX coverage on time and space scales of similar length. Specific instances of these general observations are discussed in Section 6.

iii. Superior Time Resolution

With the pulse and discontinuous nature of thunderstorms during the summer months in southeast Arizona, significant changes between volume scans of KEMX often occurred. GOES-7 imagery provided an important look at these storms but once again the time resolution was less than satisfactory. Real-time lightning data provided the best time continuity and the tracking of storms within the time gaps present in the other sources of storm scale information. In such situations, and in the future National Weather Service where mesoscale forecasting will be the main focus, the NLDN lightning data fills gaps in coverage caused by the poorer time resolution of KEMX and satellite data as well as lightning data products currently available on AFOS.

B. DETAILED COVERAGE WHEN KEMX IS OUT OF SERVICE

When KEMX was turned off for maintenance, transitioning to backup power or an unexpected failure occurred, the Phoenix WSR-88D Doppler radar (KIWA), was the primary backup. In these situations radar coverage in southeast Arizona was far from complete. Real-time lightning data provided a reliable secondary source of storm scale information when KEMX was down. Especially during summer monsoon (Douglas et al., 1993) convective events, when KEMX was out of service, lightning data were used in concert with satellite data as an effective surrogate to radar coverage. Should a major component of KEMX become disabled, it could potentially take days before the radar is brought back into full service. The satellite and lightning data in combination could prove to be a valuable resource, especially in the western states where poor radar backup coverage prevails.

6. SPECIFIC APPLICATIONS

A. BACKUP POWER DECISION FOR KEMX

Since February 1995 the operational staff at the NWSO Tucson used NLDN real-time lightning data to detect thunderstorms developing near or approaching KEMX at Tucson. A case in point occurred during the 1995 monsoon season on the evening of July 15, 1995 (Figs. 7a and 7b). Thunderstorm activity was rapidly dissipating over extreme southeast Arizona at 0600 UTC (Fig. 7a). However, an outflow boundary generated by this area of storms moved across the RDA site at about 0630 UTC and triggered a few isolated, high based thunderstorms (bases approximately 12,000 feet above ground level) within the cone of silence of KEMX (Fig. 7b). Likewise, during the daytime hours of the monsoon season, thunderstorms often developed within the cone of silence of KEMX with little or no warning.

The WSR-88D is crucial to the warning and forecast process. The WSR-88D is indispensable in analyzing severe and significant weather situations. Weather statements and advisories, aviation forecast products and virtually all short-term forecasts benefit from the analysis of the WSR-88D data. Considering the less than optimal power grid serving the area where the KEMX radar is sited, the Unit Radar Committee (URC) established the requirement that the Unit Control Position (UCP) operator is to switch from commercial to generator power whenever there is a thunderstorm within 25 miles of KEMX. The NLDN data is the primary tool to determine when this condition has been met.

At the NWSO Tucson, the real-time lightning data display software (called THUNDER) is configured to produce a series of beeps whenever a CG lightning flash is detected within 25 miles of the radar. Real-time lightning data made the backup power decision by the operational staff more timely and less stressful.

B. PUBLIC SAFETY

The NLDN lightning data provide the potential for more lead time in notifying the public of approaching thunderstorms and allow more descriptive enhancements of nowcasts and special weather statements. On several occasions since February 1995, especially during the monsoon, NLDN lightning data provided the first confirmation that a thunderstorm had developed and that CG lightning was occurring. The example from July 15, 1995 (see Figs. 7a and 7b) is a case in point when an area of weak and isolated thunderstorms containing occasional CG lightning eventually moved into the Tucson Metropolitan area.

Innocuous thunderstorms are perhaps the most dangerous in terms of lightning safety (Holle et al., 1993). During these types of storms, lightning is infrequent and can go unobserved over populated areas, especially during daylight hours. The real-time lightning data provided an extra tool on which to base special weather statements and nowcasts. An example of how lightning data was used to enhance descriptions is shown in a Special Weather Statement issued on August 13, 1995 (Fig. 8). In this case, unexpected thunderstorms developed over a region of deep outflow generated hours earlier.

The real-time lightning data facilitates the writing of proactive and specific statements about the present and near future characteristics of thunderstorms. This facilitates the effective communication of storm related details to the public.

C. BEAM BLOCKAGE

The site location of KEMX was chosen to optimize radar coverage over as much of the County Warning Area (CWA) in southeast Arizona as possible. However, due to mountainous terrain, the coverage of KEMX is inadequate. Figure 9 shows the beam occultation for KEMX due to surrounding mountains and indicates the regions in southeast Arizona that are not well covered at the lowest elevation angles. In the regions of southeast Arizona where terrain blockage knocks out the lowest elevation angles, real-time NLDN data are useful in identifying and roughly tracking the development of storms in these regions. The NWSO in Tucson has assisted the NWSFO in Phoenix using NLDN data in cases involving some of their more remote or high terrain areas.

An example of elevation angle blockage occurred on September 27-28, 1995. Thunderstorms formed in northern Mexico and moved northward into southern Pima County. Three plots of NLDN lightning data (Figs. 10a, 10b, and 10c) show first the initial CG lightning strikes detected in northern Mexico (Fig. 10a), then extensive lightning activity as the thunderstorms moved into southern portions of the CWA (Fig. 10b). Figure 10c shows the high resolution detail as these storms move through populated areas. The KEMX composite reflectivity graphic (Fig. 11) corresponding with the time that storms were first beginning to form over northern Mexico shows no indication of storms (compare to Fig. 10a). The approaching storms moved along a radial that suffers from beam blockage at the lowest elevation (see Fig. 9). The NLDN loop clearly showed what was happening, confirmed later by the lower time resolution satellite data. The NLDN data allowed the forecaster to have the longest lead time possible and the public was well served.

D. STORM TENDENCIES AND STRUCTURE

Real-time lightning data provides a nearly instantaneous indication of storm tendencies and cycles, including the initiation and dissipation of convection (Holle et al., 1994; Stolzenburg 1994; Watson et al., 1991; Lopez et al., 1990; Mosher 1989; Lopez et al., 1989). The update rate of real-time lightning data supplied by the NLDN surpasses all other meteorological data currently available at NWSO Tucson including satellite, surface observations, Automated Local Evaluation in Real-Time (ALERT) rain-gage data, and even WSR-88D data. The two cases that follow demonstrate the applicability of real-time lightning data to the short term forecast and warning operations of NWSO Tucson.

i. August 19, 1995: Organization and dissipation of a tropical squall line.

During the period 2000 - 2300 UTC 19 August 1995, thunderstorms primarily rooted over the higher terrain of southeast Arizona, began to organize into a mesoscale convective system (MCS) from central Arizona to northern Sonora, Mexico. These storms developed into what could be considered a tropical squall as described by Smith and Gall (1989). Figures 12a and 12b show the base reflectivity from KEMX at 2128 UTC 19 August 1995 during the development phase, and at 0036 UTC 20 August 1995 during the mature phase of the MCS, respectively.

A closer look at the lightning activity over the NWSO Tucson county warning area is shown in Figs. 13 (a - f). In Figs. 13 (a - c) are the negative flashes (km^{-2} hr^{-1}) for the 2 hour periods ending at 0000, 0200 and 0400 UTC, respectively. At 0000 UTC, two areas of lightning activity are shown: the first over the southeast corner of Arizona representing redevelopment of convection (mainly over higher terrain) behind the MCS; and the second area associated with the MCS extending from just west of Globe, Arizona (GLB) to just west of Tucson to around Nogales, Arizona (NGL). By 0200 UTC, the 2 hourly lightning rates have increased and become more solid over much of central and eastern Pima County. And by 0400 UTC, the 2 hourly rates decreased rapidly as the MCS dissipated with little new negative CG lightning activity noted. Similarly, shown in Figs. 13 (d - f) are the positive flash rates (km^{-2} hr^{-1}) for the same time period. Note the evolution of the positive flashes, developing primarily from north to south during the period. Over the NWSO Tucson CWA, 2 hourly positive flash density rates increase in the 0200 and 0400 UTC time frames as the MCS dissipated (Fig. 13e and f). It appears that the charge of the lightning may aid real-time operational analysis of convective situations by providing information on the maturity of the convective system, specifically as positive flashes occur when precipitation evolves from predominantly convective to predominantly stratiform (Holle et al. 1994; Stolzenburg 1994; Houze 1993; Lopez et al. 1990).

ii. September 27-28, 1995: Nocturnal Thunderstorm Development over Northern Mexico

Supercell thunderstorms are a rare occurrence in Arizona. This can be inferred from the low frequency of very large hail and/or significant tornadoes reported in the climatological records. However, during the late evening hours of September 27, 1995, thunderstorms developed rapidly over northern Mexico in an unstable environment favorable for potential supercell formation. Approximately 50 knots of unidirectional wind shear existed within the lowest 5 km of the atmosphere, a sufficient condition for supercell thunderstorms (Weisman and Klemp 1982). Meanwhile, a weak upper-level trough was forecast to approach southern Arizona during the night. Numerical guidance was generally poor at suggesting to the forecasters that a potential for thunderstorms existed that night. Thus, their development was generally considered a surprise to the forecasters at the NWSO Tucson.

The NLDN lightning data provided the first indication that storms developed (as discussed in Section 6C) and more importantly that storms had developed over northern Mexico. The KEMX radar was initially deficient in the storm detection due to the distance of the storms from the radar, since the lowest elevation angle critical for distant storm detection are completely blocked by terrain to the southwest. Figure 14a shows the composite reflectivity at 0530 UTC on September 28, while Fig. 14b shows the one hour lightning activity between 0515 and 0615 UTC. The eastern cluster of lightning is disorganized and is clearly associated with the 50 dBz returns south of Nogales, Arizona. However, the western cluster of lightning shows splitting storm cell organization but the maximum reflectivity is only 20 dBz due to the terrain blockage. In Figs. 15a and 15b are the corresponding radar and lightning detection images one hour later as the storms were moving into southern Arizona. Thunderstorms possessing cores with reflectivities greater than 60 dBz were being detected by KEMX at 0629 UTC, but note how nicely the lightning complimented KEMX by showing the tendency for storms to split during this event. However, due to the lowest elevation angle remaining blocked by the terrain, KEMX algorithms were still operating at a degraded level and did not indicate a mesocyclone. Storm 36 soon produced baseball sized hail (spotter report and later verified) as it moved into southern Arizona.

E. LOW-TOP CONVECTION

The real-time NLDN data can be very useful in low-topped convective outbreaks. A specific example occurred on November 15, 1995. At 1200 UTC on November 15, 1995, a cut-off low was located across northern Baja California and the Sonoran district of northwest Mexico (Fig. 16). This cut-off low continued to move slowly east to just south of Nogales, Arizona through 0000 UTC Wednesday afternoon. The cut-off low produced a moderately unstable atmosphere favorable for the development of weak thunderstorms especially south of Douglas, Arizona.

KEMX experiences beam blockage in the lowest elevation angles over southern Cochise County (see Fig. 9). This is most evident with low-topped convection. Tops in this case were lower than 25,000 feet and KEMX was not able to detect them. *No useful information, related to these low top storms, was available via radar!* Infrared satellite imagery showed that clouds were developing over the region but whether those clouds contained thunderstorms was not clear. Any information concerning thunderstorm activity is especially critical to aviation where even weak high based storms can have an extreme impact. With the use of real-time NLDN lightning data (Fig. 17), thunderstorms were quickly and unambiguously identified. This allowed the timely update of the southeast Arizona zone, terminal and flight route forecasts for Douglas. The NLDN data took speculation out of the decision process and improved service to National Weather Service customers.

F. MEXICAN DATA COVERAGE

Presented in Fig. 18 is a regional depiction of the lightning activity associated with the MCS described in Section 6D. The lightning shows convective organization from central Arizona through southern Arizona into Sonora, Mexico. This figure serves to demonstrate two important features associated with operational application of real-time lightning detection. First, real-time lightning data provides another tool for the meteorologist to use in assimilating the synoptic and mesoscale state of the atmosphere. Second, with no radar data available over Mexico (nor the surrounding coastal waters of the United States), real-time lightning data provides information on convection over remote areas. Detection efficiency and location accuracy decrease away from the contiguous United States borders (as discussed in Section 4), but Fig. 18 illustrates that it still provides useful information in regions of decreased detection efficiency. Thus, the only real-time data available from Mexico is satellite imagery, and in convective situations these pictures are often obscured by high cloudiness. Frequently, real-time lightning data are the only data confirming convective development over Mexico. The case of September 27-29, 1995 in Section 6D provides an excellent example of this.

G. NATIONAL COVERAGE

Real-time lightning data provided the staff at NWSO Tucson with convenient and concise national coverage of convection around the United States. These data help simplify the national convective picture for forecasters and hydrometeorological technicians, despite the availability of other data such as that from KEMX. Rather than using the coarse lightning data product available on AFOS (NMCGPHLDS), one glance at the national NLDN map provides a snap-shot of convective activity around the country. This is demonstrated in Figs. 19a and 19b. In Fig. 19a are lightning strikes for the 6 hour period ending on August 3, 1995 at 0000 UTC while in Fig. 19b is the daily surface weather map from August 2, 1995 at 1200 UTC. Convection along a stationary front through the central part of the United States is clearly defined, as is a band of convection along and ahead of the cold front moving through the Northern Plains, convection associated with a tropical storm over Florida, and widely scattered thunderstorms over the Intermountain region. Note how quickly the NLDN national map provides the forecaster with real-time detail regarding the convective situation around the country, complimenting the surface analysis while simplifying weather briefings to meteorologists and customers.

7. RESEARCH APPLICATIONS AND CLIMATOLOGY

Lightning data has provided the staff at NWSO Tucson with another dataset for the post-analysis of significant weather events. Examples of this application have been demonstrated in Section 6. The following research applications are more general, and illustrate potential long-term applications for lightning data.

A. CLIMATOLOGY

Typically, the monsoon over Arizona begins by the middle of July and lasts into September (See Maddox et al., 1995 Section 2b for a climatological discussion of the monsoon over Arizona). However, the monsoon of 1995 was late with minimal activity over Arizona until August. It wasn't until nearly the middle of August that widespread convective precipitation occurred on a near-daily basis. Figures 20 (a - c) illustrates the point showing 10-day composite lightning strikes (contoured at 0.5 flashes km^{-2}) over most of the NWSO Tucson CWA. In Fig. 20a are lightning strikes for the period 0000 UTC August 1 through 0000 UTC August 11, 1995. Note that flash densities are generally below 0.5 flashes km^{-2} over most of the area, with the exception of three localized maxima over southern Arizona, most notably near Nogales (NGL). But, during the next 10-day period (0000 UTC August 11 - 0000 UTC August 21, 1995) shown in Fig. 20b, flash densities dramatically increased over the entire area with a large region in excess of 0.5 flashes km^{-2}, and a few pockets in excess of 2 flashes km^{-2}. The final 10-day period of August (0000 UTC August 21 - 0000 UTC September 1, 1995) shows less activity (Fig. 20c) than the middle of the month, but considerably more widespread activity than the first 10 days of the month. In this case, compositing the lightning strikes over southern Arizona helps depict the evolution of the monsoon during the month of August.

Compositing can be done seasonally, as discussed above, or annually as shown in Fig. 21 (courtesy of Raul Lopez and Ron Holle, NSSL). Figure 21 provides a concise indicator of the annual lightning flash density over the state of Arizona for June through September for an 8 year period (1987-94). The flash density is maximized along the Mogollon Rim over east central Arizona, with a secondary maximum over southeast Arizona.

B. CONVECTIVE RAINFALL INDICATOR

Lightning data could be used as another tool to aid in the estimation of rainfall over data sparse locations. During the summer months in Arizona, nearly all rainfall is convective in nature. Watson et al. (1994) showed that in Arizona during the months of June through September there is good correlation between the number of CG strikes observed within a 400 km^2 area surrounding a particular rain gage and the number of days where measurable rain was received at each rain gage. So there probably is at least *some* correlation between lightning flash density and rainfall accumulations; however, the authors are unaware of any documentation which attempts to quantify CG vs. rainfall relationships.

Figure 22a shows the preliminary analysis of July 1995 rainfall over the state of Arizona as provided by the Office of the State Climatologist in their publication *Arizona Climate Summary*. These data are considered preliminary as the purpose of the publication is to provide an early summary of the past month's weather. Since timeliness is critical, frequently only the first order weather observing stations are used in their analyses. Figure 22a shows that Douglas received 3.22 inches of rain (0.19 inches below normal) while about 75 miles to the west, Nogales only received 0.33 inches for July, 1995 (4.62 inches below normal). The objective analysis routine used to contour the analysis shows a nearly linear change in departure from normal between Nogales and Douglas, with the 2 inch below normal contour approximately between Douglas and Nogales. However, the lightning data composited for the month of July (Fig. 22b) indicates two maxima in the flash density over southern Arizona: one just north of Douglas, and a second of equal magnitude approximately half way between Douglas and Nogales (this second maximum is over the Huachuca mountains). The maximum just north of Douglas correlates well with the precipitation maximum in the region reported from the Douglas observation site. However, it is likely that another precipitation maximum exists between Douglas and Nogales in the vicinity of the Huachuca Mountains, in the area of the equally strong second CG lightning maximum.

The intent here is not to criticize the preliminary analysis, but rather illustrate the potential of lightning data as an aid in timely precipitation estimation over data-void regions.

8. ACKNOWLEDGMENTS

The authors would like to thank Ron Holle, Raul Lopez, Bob Maddox, Bill Geitz and Andy Bryant for their reviews and constructive suggestions concerning this manuscript. We are also thankful to GAI for allowing the NWSO at Tucson to use NLDN data in the office since February of 1995. Without this data a real-time evaluation would not have been possible. Thanks goes to our Meteorologist In Charge Marv Shogren, Warning Coordination Meteorologist Paul Flatt and Data Acquisition Program Manager Paul Crimmins for their support and the willingness to make time for this project to be completed. Finally, we would like to thank the forecasters at the NWSO Tucson for their input and comments regarding the uses of real-time lightning data.

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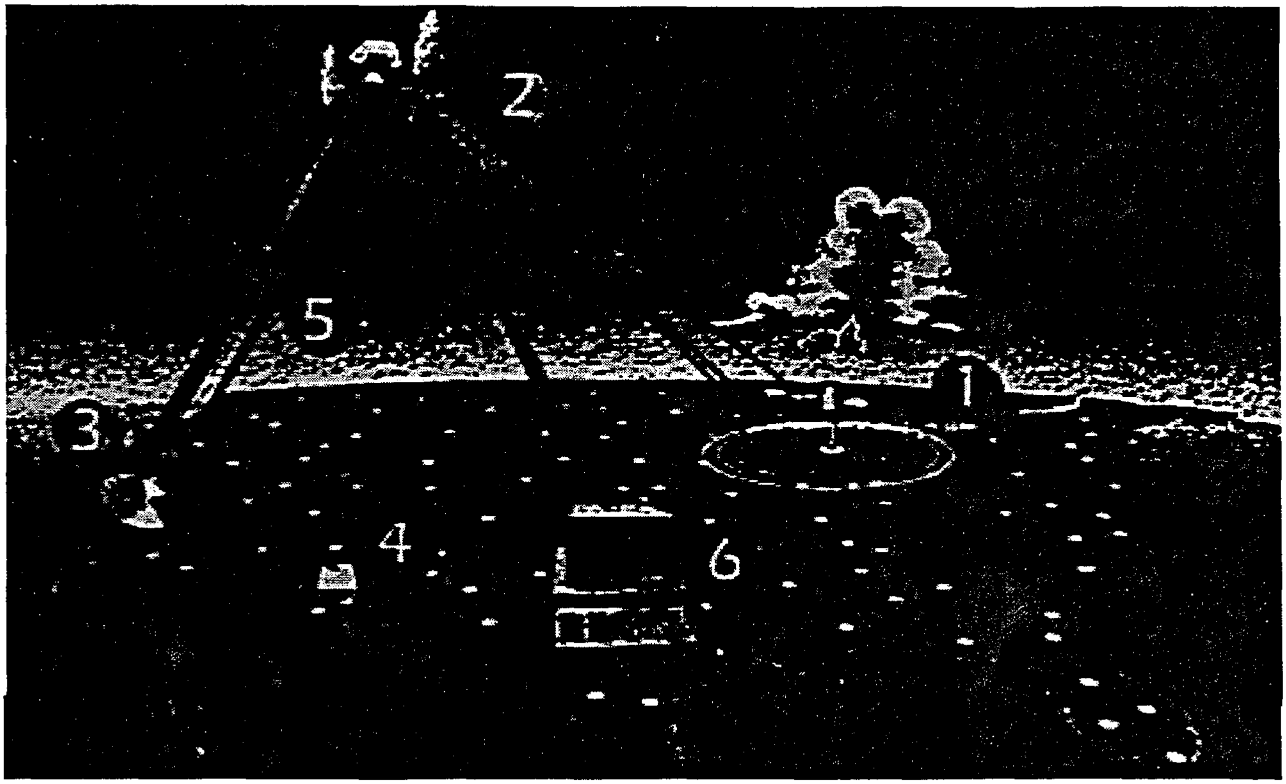


Figure 1: The systems configuration for the NLDN from data collection to distribution of real-time data to users. Ground-based sensors detect the electromagnetic signal produced by a lightning discharge (1) and transmit salient information to the Network Control Center (NCC) in Tucson, Arizona via a two-way satellite system (2-3). This "raw" data from the remote sensors is processed at the NCC (4) to provide the time, location and peak current of each detected discharge. This processed information is sent back to the communications network for satellite broadcast dissemination (5) to real-time users (6). All this takes place within 30-40 seconds of a lightning flash (from Cummins 1995).

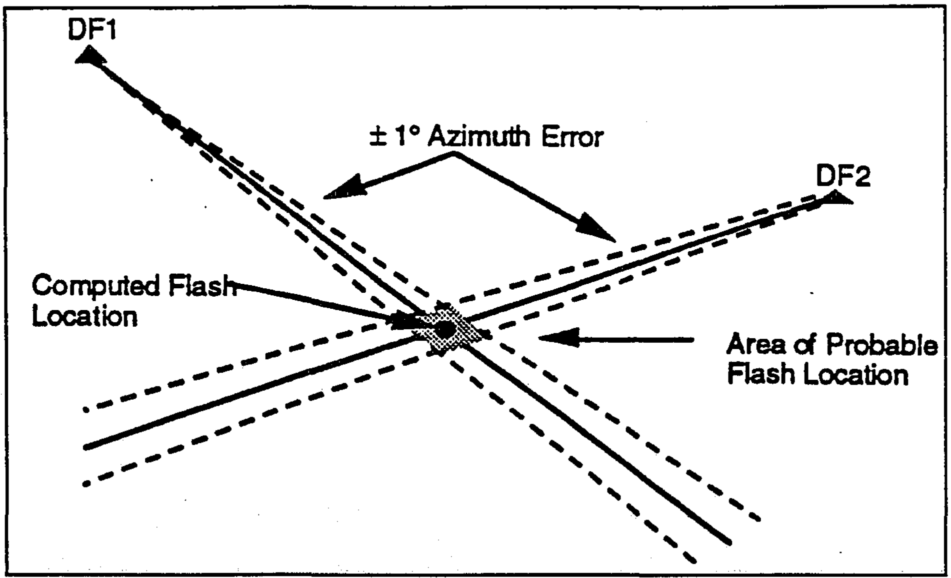


Figure 2a: Determination of cloud-to-ground flash loction when two DFs detect it. Solid lines represent measured azimuth of the flash; dashed lines outline the angular random error in azimuth measurements. Dot indicates computed flash location; shaded indicates area where flash probably occurred (from Holle and Lopez 1993).

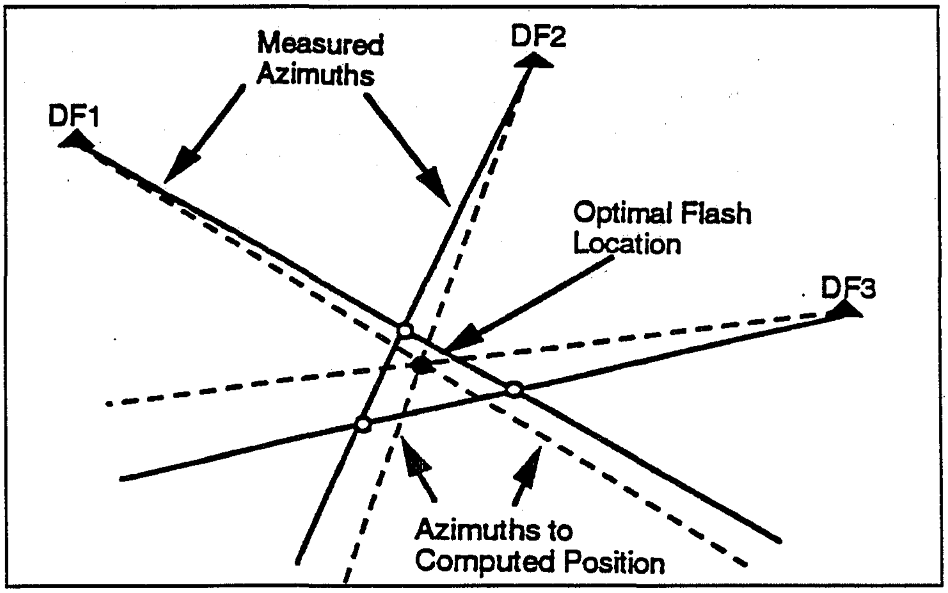


Figure 2b: Determination of flash location when three DFs detect it. Solid lines represent measured azimuths of flash. Open circles indicate the three possible locations defined by three different intersections of azimuth vectors. The position (solid dot) that would minimize the square differences between measured azimuths (solid lines) and computed azimuths (dashed lines). From Holle and Lopez 1993.

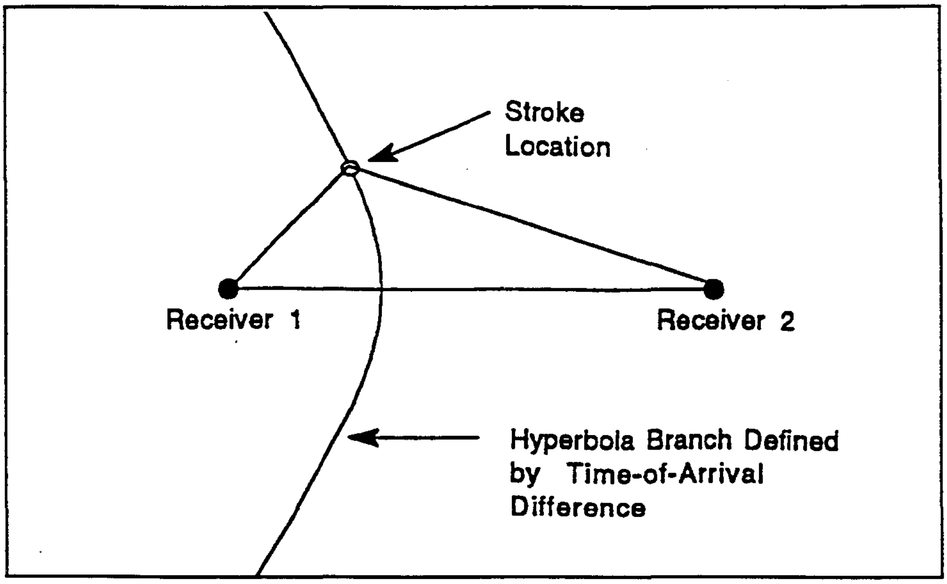


Figure 3a: Detection of a cloud-to-ground lightning stroke by two TOA receivers. For a given time-of-arrival difference, the stroke that emitted the signal could be located anywhere along one of the branches of a hyperbola that passes between the two receivers and has as foci the two receiver locations (from Holle and Lopez 1993).

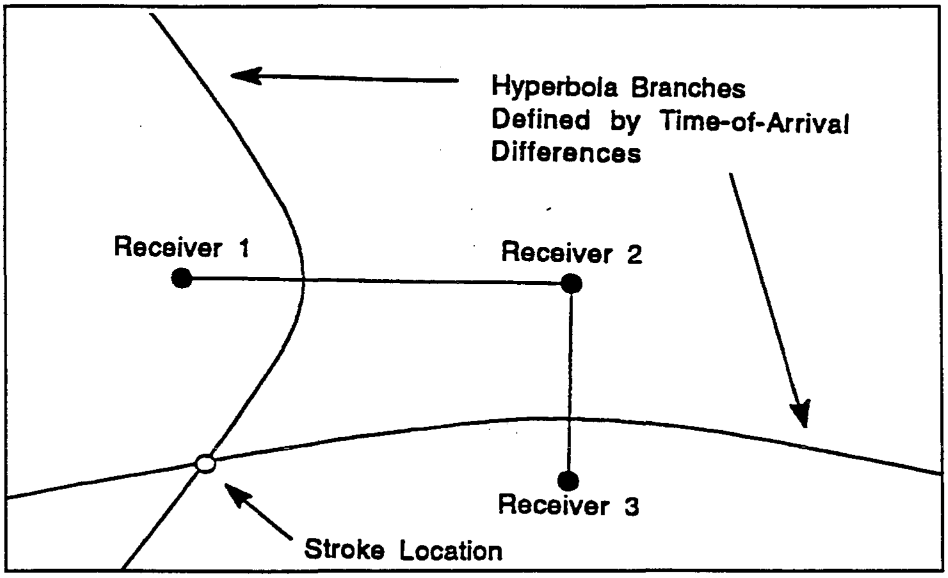


Figure 3b: Detection of a cloud-to-ground lightning stroke by three TOA receivers. Two non-redundant hyperbola branches are defined whose intersection can define the location of the stroke (open circle). From Holle and Lopez 1993.

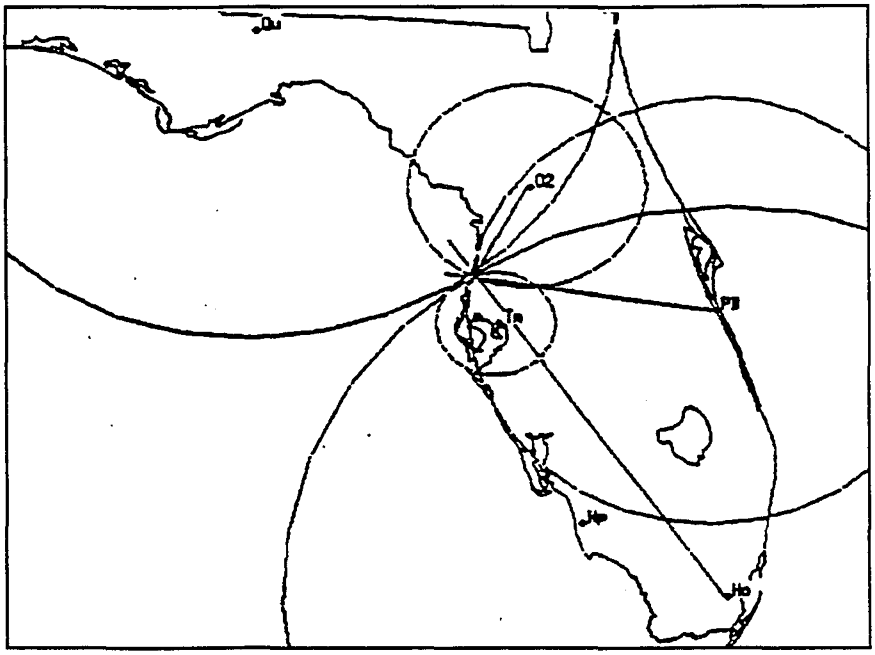


Figure 4: Example of a lightning stroke located by two LPATS sensors and three IMPACT sensors. Straight lines are azimuth vectors (i.e., DF) and circles are the solution radii (i.e., TOA). Figure from Cummins 1995.

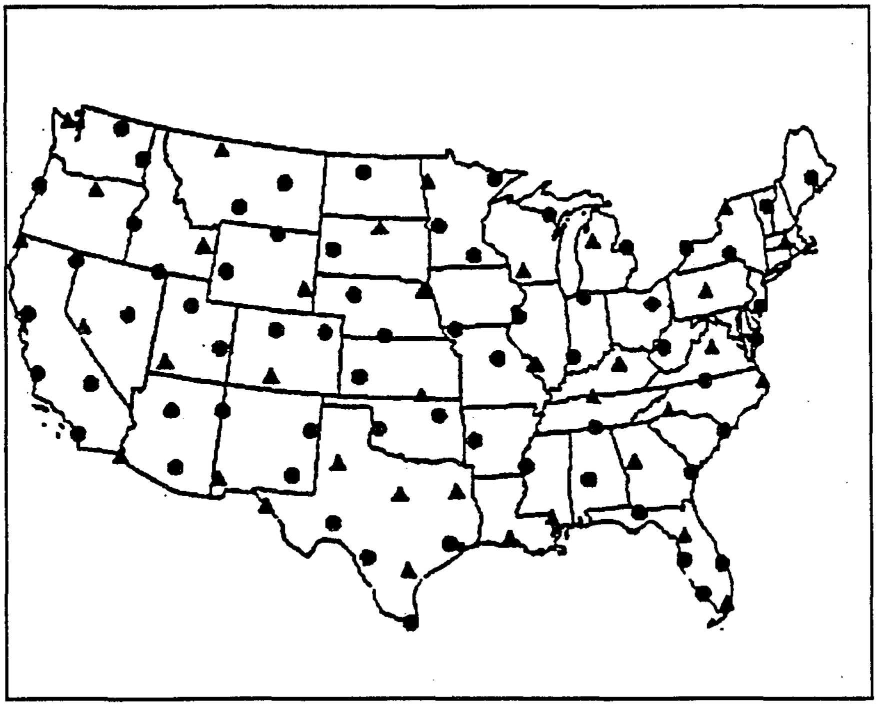


Figure 5: The NLDN sensor locations within the contiguous United States. Triangles represent IMPACT sensors; circles represent LPATS sensors.

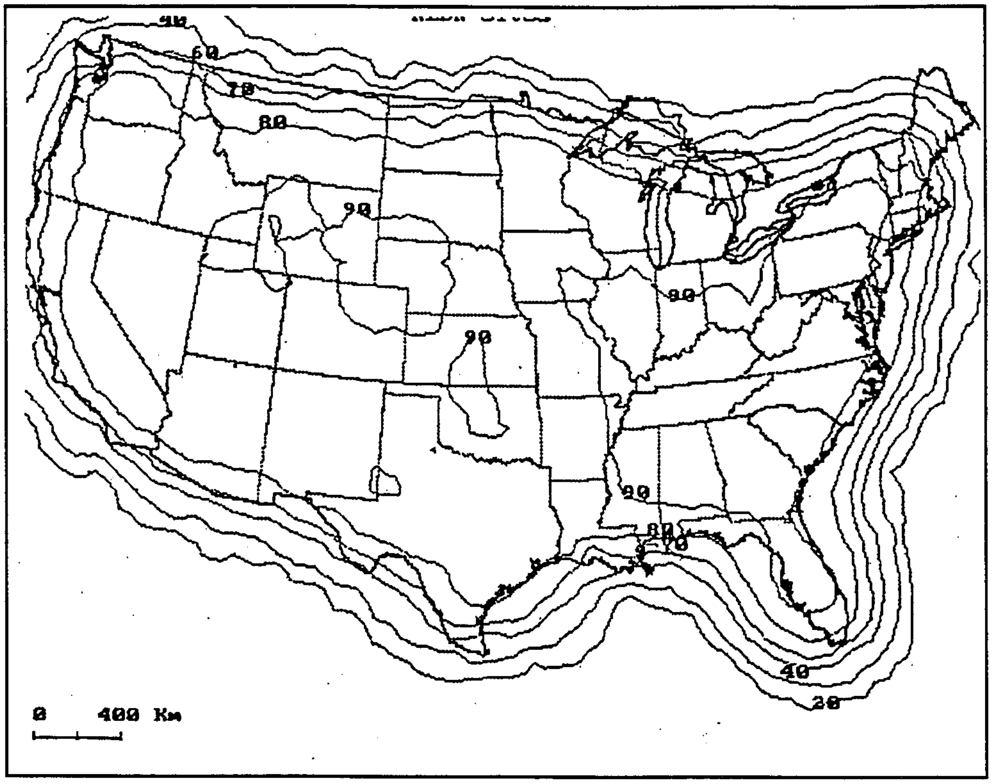


Figure 6a: The NLDN cloud-to-ground lightning detection efficeincy for the contiguous United States. Contours indicate detection efficeincy in percentage (Cummins 1995).

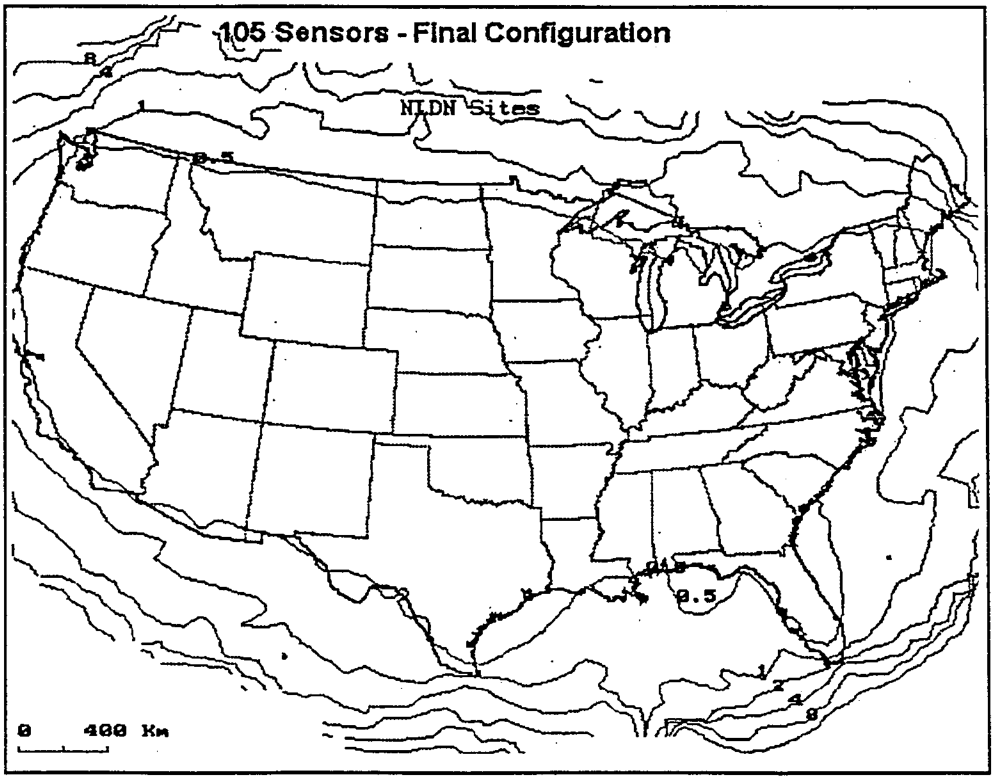


Figure 6b: Approximate cloud-to-ground lightning location accuracy of the NLDN for the contiguous United States and surrounding area. Contours indicate the uncertainty radius (in km) of a plotted lightning strike (Cummins 1995).

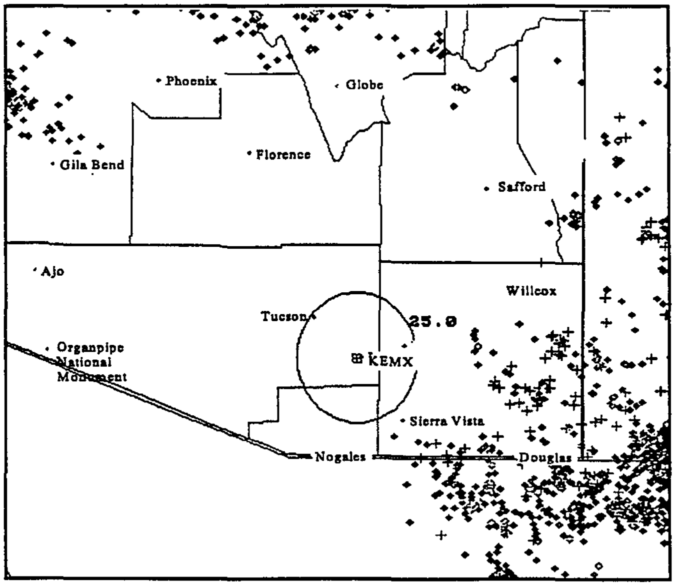


Figure 7a: NLDN data from July 15, 1995 between 0500 and 0600 UTC. Positive strikes are indicated by plus signs, negative strikes are indicated by diamonds. Large circle indicates 25 mile radius surrounding KEMX.

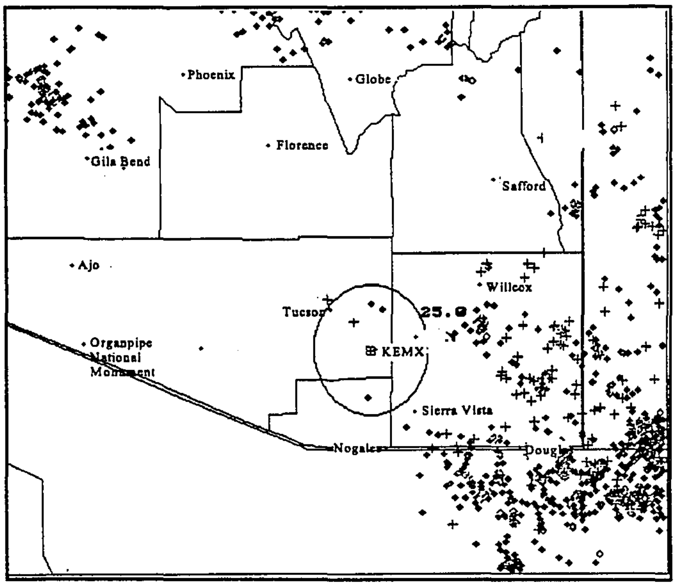
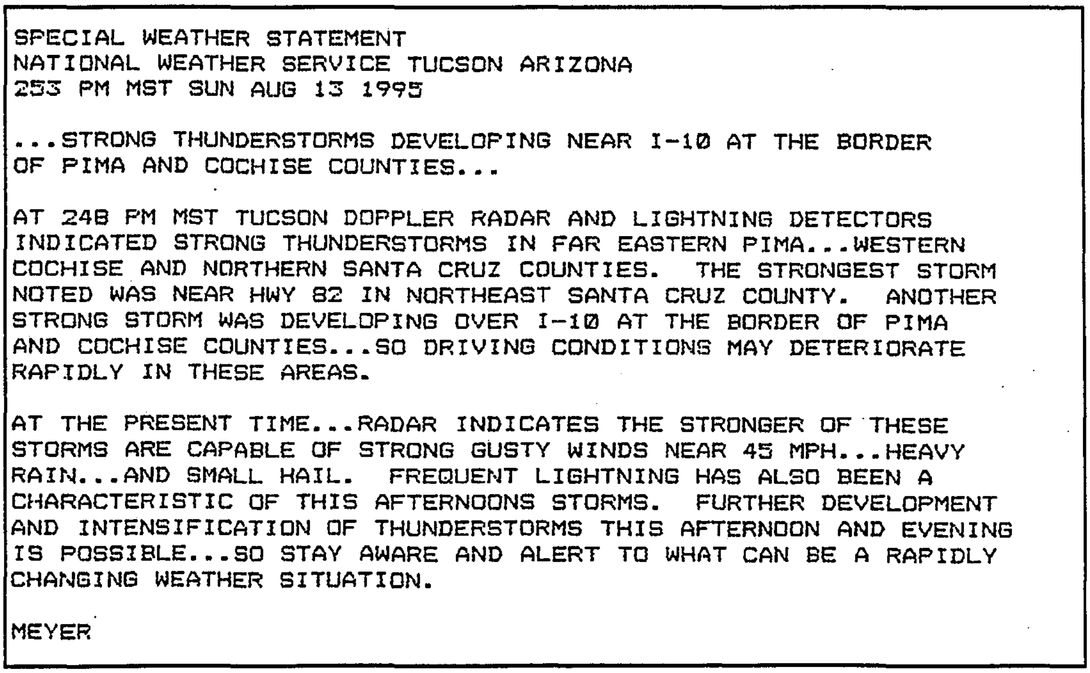


Figure 7b: Same as Fig. 7a except between 0500 and 0700 UTC.



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SPECIAL WEATHER STATEMENT
NATIONAL WEATHER SERVICE TUCSON ARIZONA
253 PM MST SUN AUG 13 1995

...STRONG THUNDERSTORMS DEVELOPING NEAR I-10 AT THE BORDER
OF PIMA AND COCHISE COUNTIES...

AT 248 PM MST TUCSON DOPPLER RADAR AND LIGHTNING DETECTORS
INDICATED STRONG THUNDERSTORMS IN FAR EASTERN PIMA...WESTERN
COCHISE AND NORTHERN SANTA CRUZ COUNTIES.  THE STRONGEST STORM
NOTED WAS NEAR HWY 82 IN NORTHEAST SANTA CRUZ COUNTY.  ANOTHER
STRONG STORM WAS DEVELOPING OVER I-10 AT THE BORDER OF PIMA
AND COCHISE COUNTIES...SO DRIVING CONDITIONS MAY DETERIORATE
RAPIDLY IN THESE AREAS.

AT THE PRESENT TIME...RADAR INDICATES THE STRONGER OF THESE
STORMS ARE CAPABLE OF STRONG GUSTY WINDS NEAR 45 MPH...HEAVY
RAIN...AND SMALL HAIL.  FREQUENT LIGHTNING HAS ALSO BEEN A
CHARACTERISTIC OF THIS AFTERNOONS STORMS.  FURTHER DEVELOPMENT
AND INTENSIFICATION OF THUNDERSTORMS THIS AFTERNOON AND EVENING
IS POSSIBLE...SO STAY AWARE AND ALERT TO WHAT CAN BE A RAPIDLY
CHANGING WEATHER SITUATION.

MEYER
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Figure 8: Special weather statement for southeast Arizona from August 13, 1995.

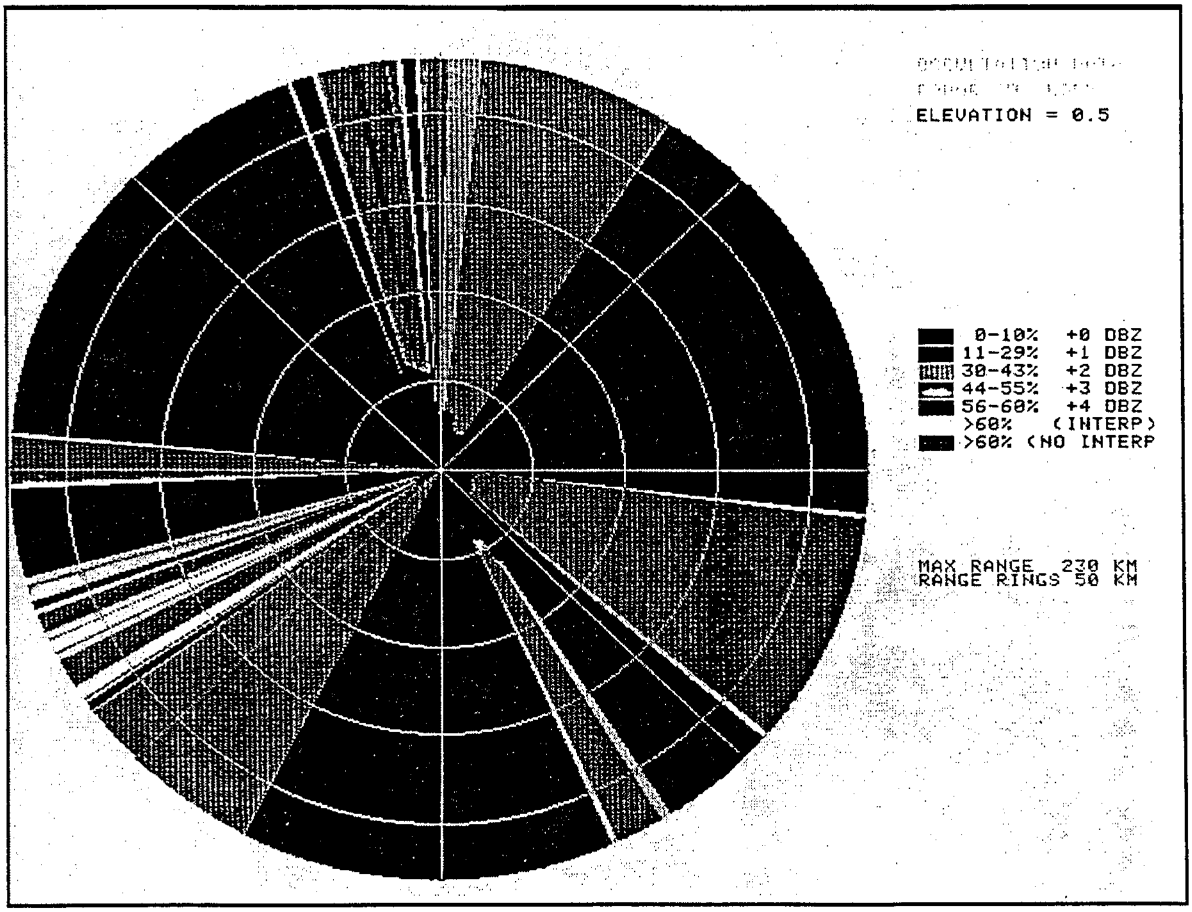


Figure 9: Occultation data for KEMX at Tucson. The lighter shades of gray indicate regions where the 0.5 degree elevation scan of KEMX is blocked by local topography.

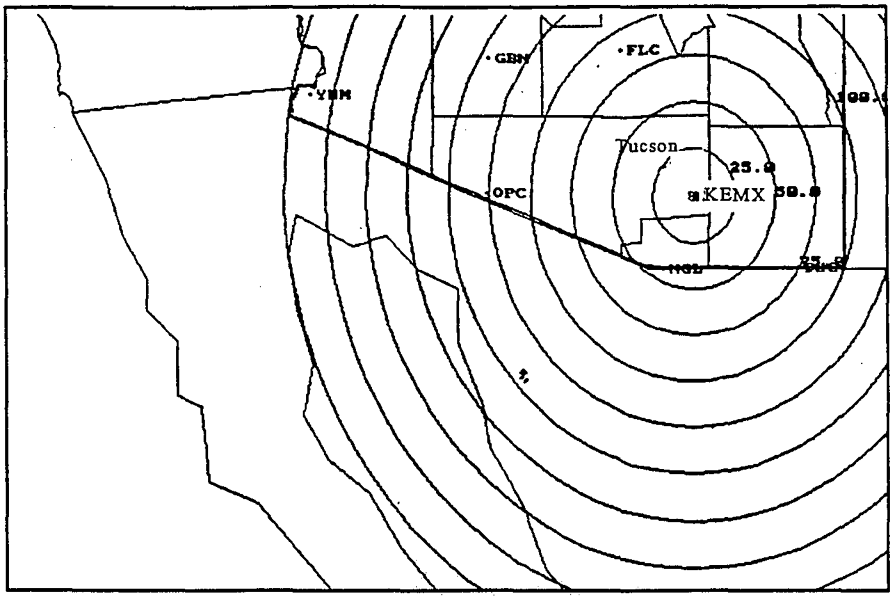


Figure 10a: Initial cloud-to-ground lightning strikes detected by the NLDN from the September 27-28, 1995 storm at 0515 UTC.

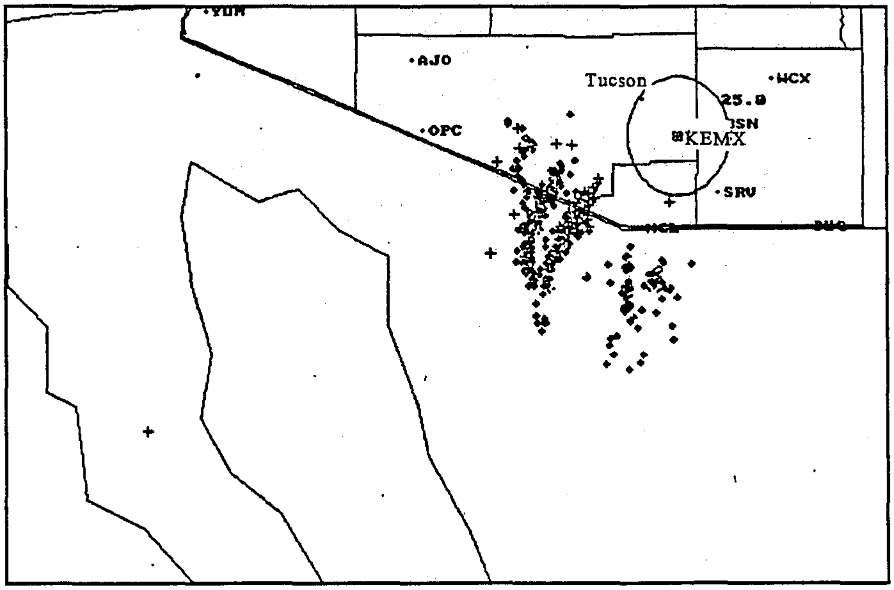


Figure 10b: Cloud-to-ground lightning strikes between 0515 and 0700 UTC as the storm of September 27-28 developed and strengthened.

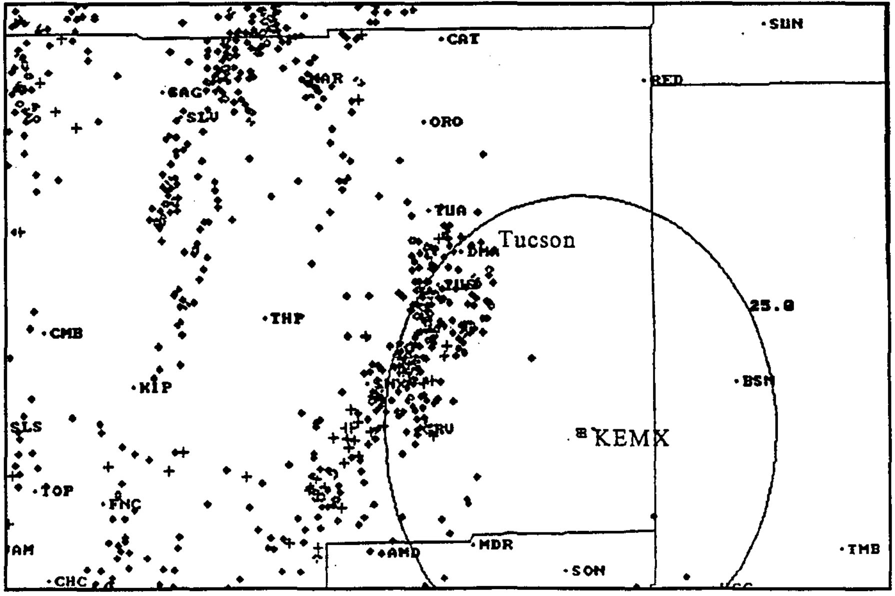
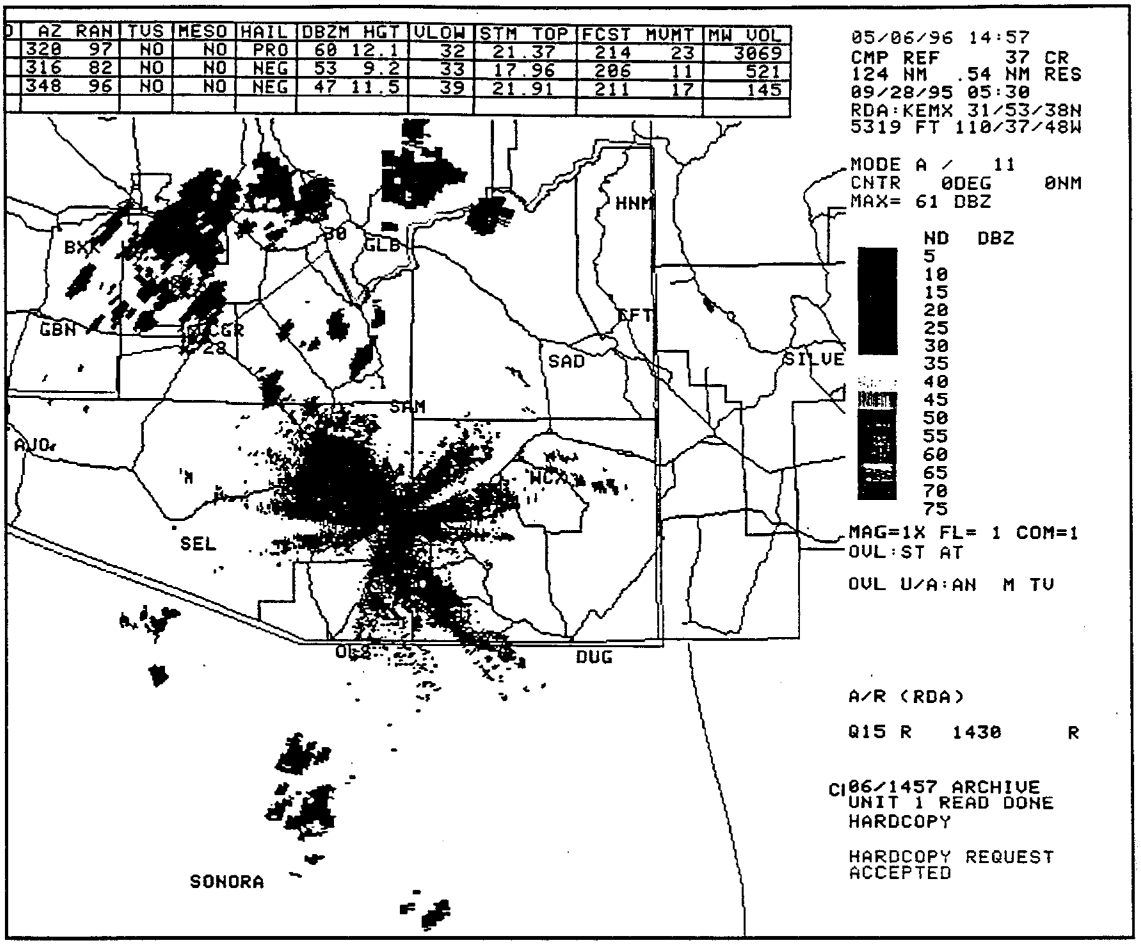


Figure 10c: Cloud-to-ground lighting history between 0800 and 0830 UTC during the time of heaviest rain in Tucson.



D	AZ RAN	TVS	MESO	HAIL	DBZM HGT	VLOW	STM TOP	FCST MVMT	MW VOL
	320 97	NO	NO	PRO	60 12.1	32	21.37	214 23	3069
	316 82	NO	NO	NEG	53 9.2	33	17.96	206 11	521
	348 96	NO	NO	NEG	47 11.5	39	21.91	211 17	145

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05/06/96 14:57
CMP REF       37 CR
124 NM   .54 NM RES
09/28/95 05:30
RDA:KEMX 31/53/38N
5319 FT 110/37/48W

MODE A /    11
CNTR    0DEG     0NM
MAX= 61 DBZ

ND   DBZ
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
MAG=1X FL= 1 COM=1
OVL:ST AT

OVL U/A:AN   M TV


A/R (RDA)

015 R   1430      R

C106/1457 ARCHIVE
UNIT 1 READ DONE
HARDCOPY

HARDCOPY REQUEST
ACCEPTED
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Figure 11: Composite reflectivity product from KEMX for September 27-28, 1995 at 0530 UTC.

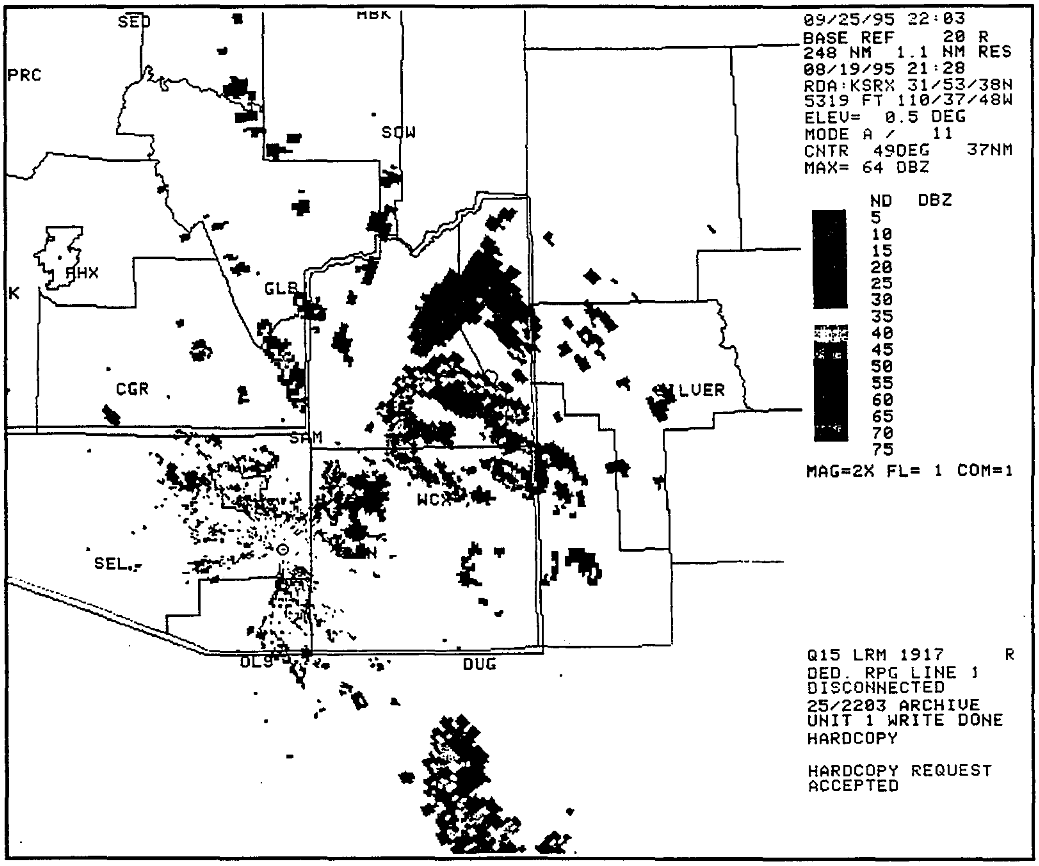


Figure 12a: The 0.5 degree base reflectivity for KEMX. Depicted is the initiation phase of the tropical squall line at 2128 UTC August 19, 1995.

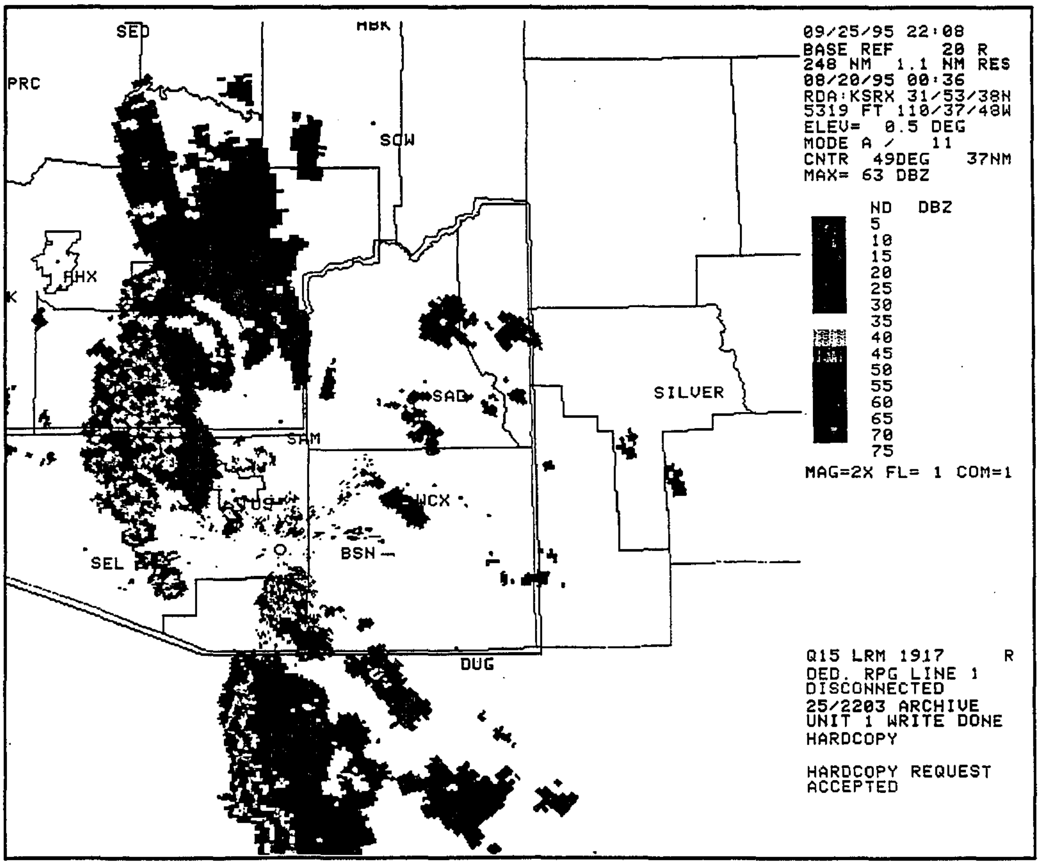


Figure 12b: Same as in (a) except for 0036 UTC. Mature phase of the tropical squall line.

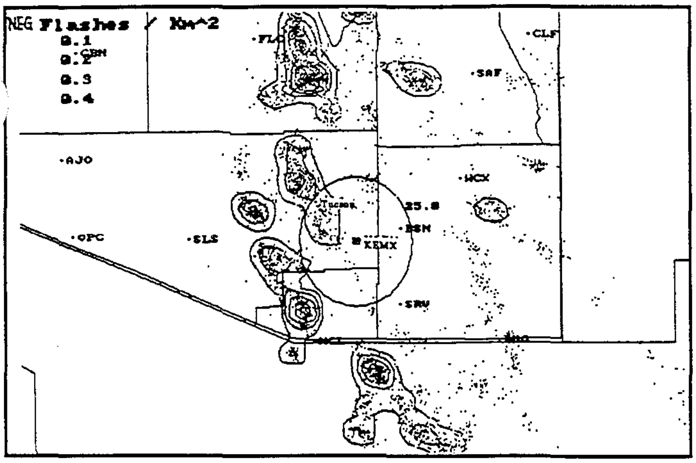


Figure 13a: Negative flashes for the two hour period ending at 0000 UTC August 20, 1995 with contoured flash density (km^{2}hr^{-1}). Figure (a) through (f) shows the history of cloud-to-ground flashes for the August 19, 1995 storm.

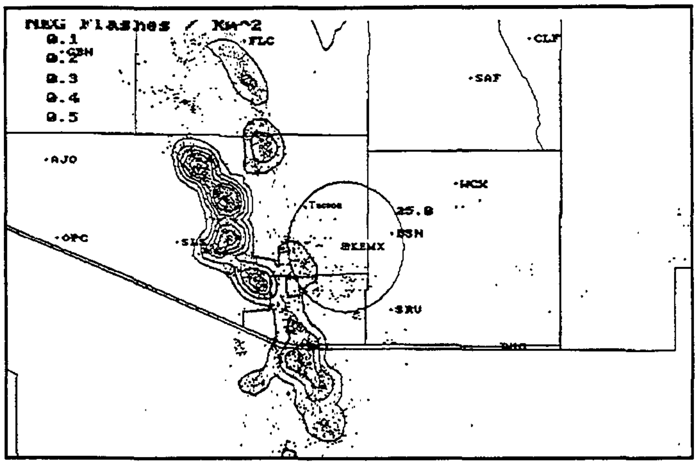


Figure 13b: Same as in (a) except ending at 0200 UTC.

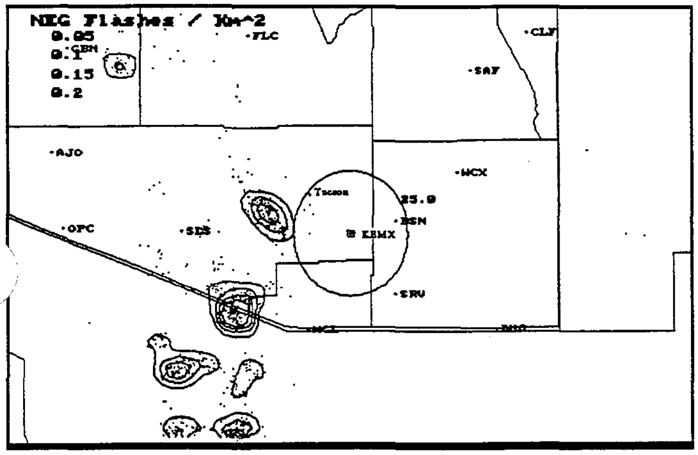


Figure 13c: Same as in (a) except ending at 0400 UTC.

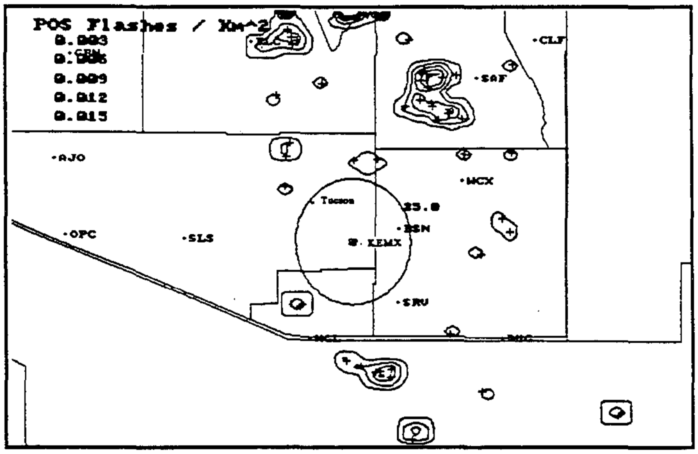


Figure 13d: Positive flashes for the two hour period ending at 0000 UTC August 20, 1995 with contoured flash density (km^{2}hr^{-1}).

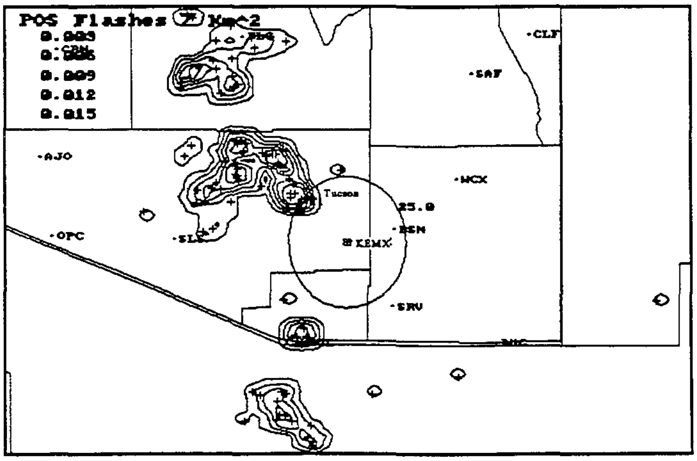


Figure 13e: Same as in (d) except ending at 0200 UTC.

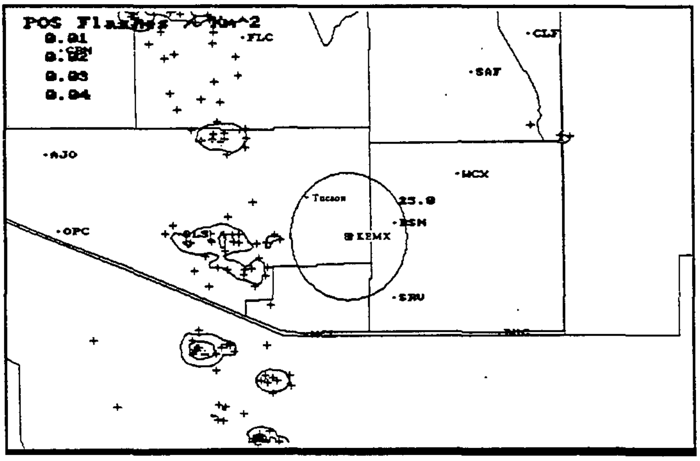
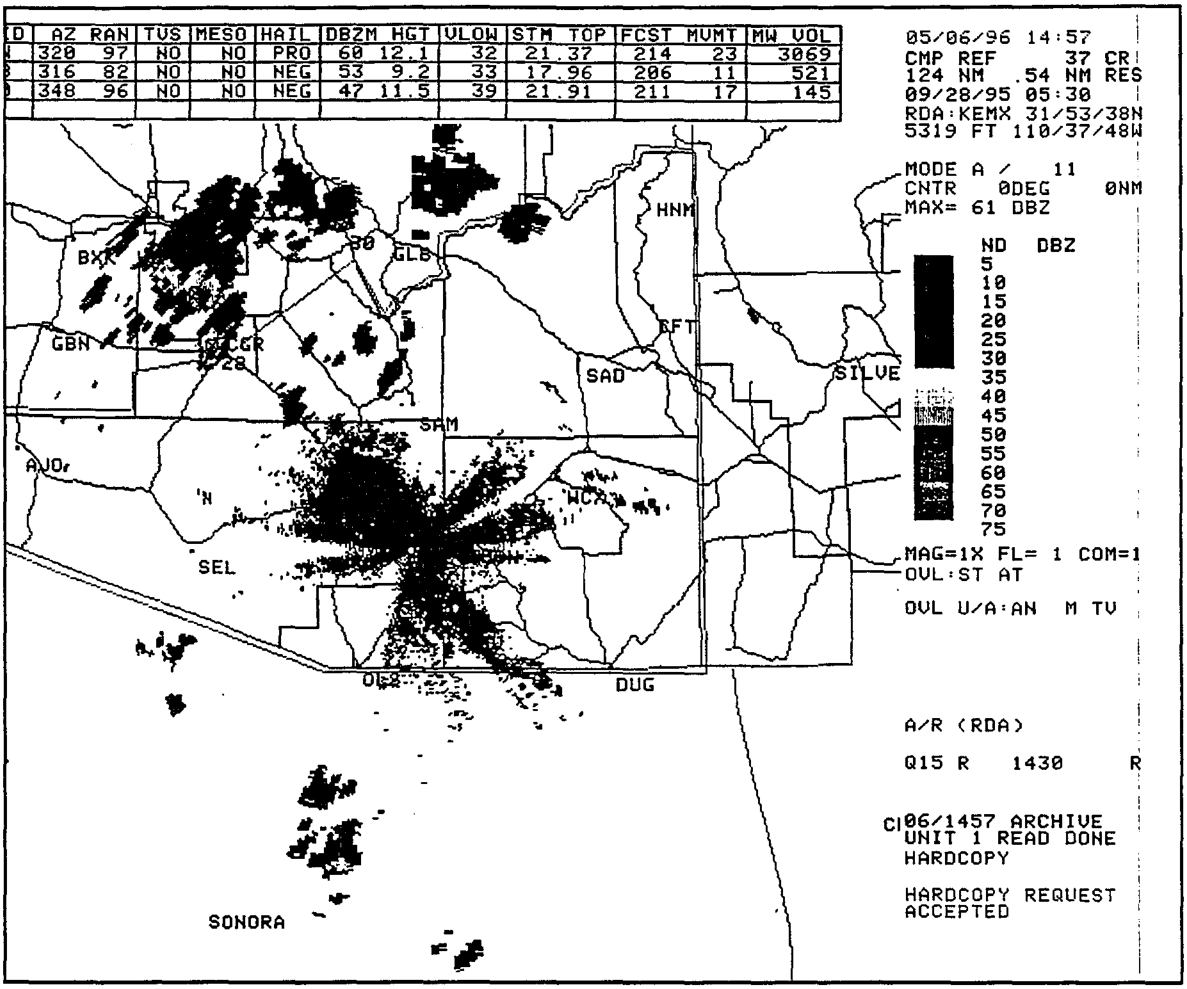


Figure 13f: Same as in (d) except ending at 0400 UTC.



ID	AZ RAN	TVS	MESO	HAIL	DBZM HGT	VLOW	STM TOP	FCST MVMT	MW VOL
	320 97	NO	NO	PRO	60 12.1	32	21.37	214 23	3069
	316 82	NO	NO	NEG	53 9.2	33	17.96	206 11	521
	348 96	NO	NO	NEG	47 11.5	39	21.91	211 17	145

```
05/06/96 14:57
CMP REF       37 CR
124 NM   .54 NM RES
09/28/95 05:30
RDA:KEMX 31/53/38N
5319 FT 110/37/48W

MODE A /    11
CNTR   0DEG      0NM
MAX= 61 DBZ

     ND  DBZ
     5
     10
     15
     20
     25
     30
     35
     40
     45
     50
     55
     60
     65
     70
     75
MAG=1X FL= 1 COM=1
OVL:ST AT

OVL U/A:AN   M TV


A/R (RDA)

Q15 R   1430      R

CI06/1457 ARCHIVE
UNIT 1 READ DONE
HARDCOPY

HARDCOPY REQUEST
ACCEPTED
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Figure 14a: Composite reflectivity from KEMX on September 27-28, 1995 at 0530 UTC showing the poor coverage of storms developing to the southwest in Mexico.

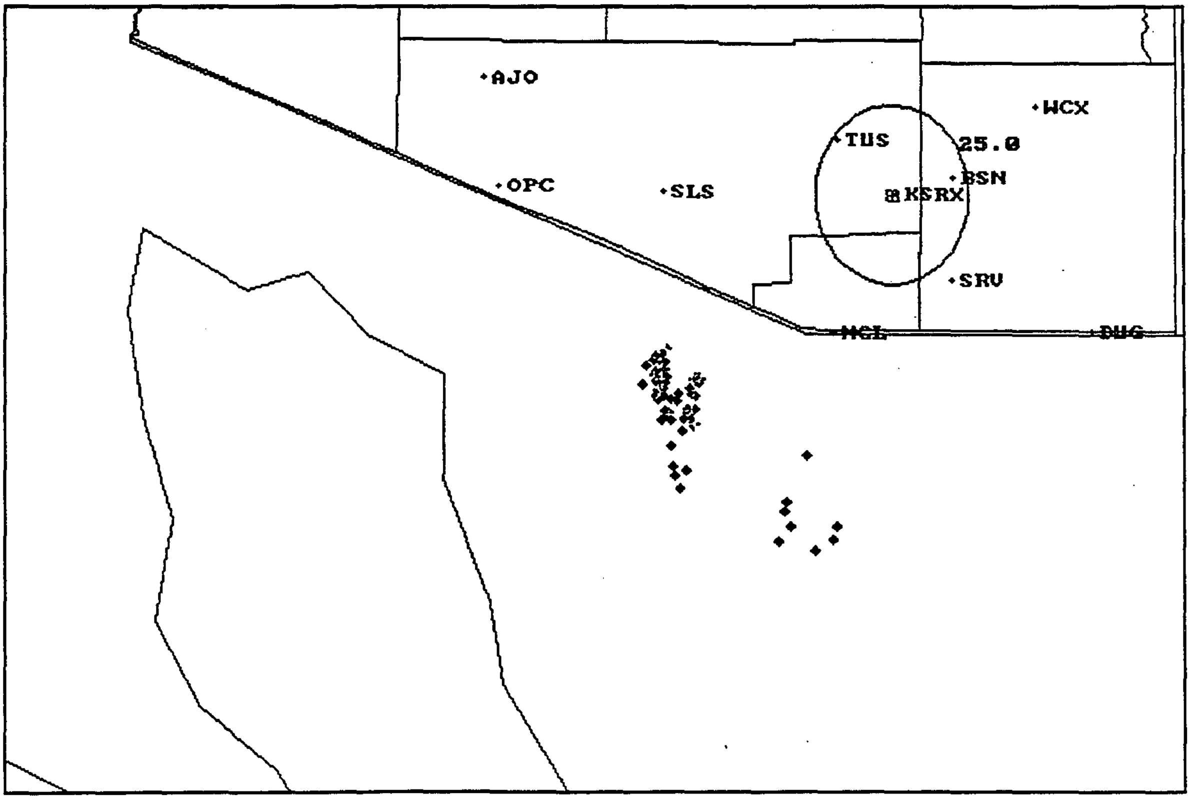
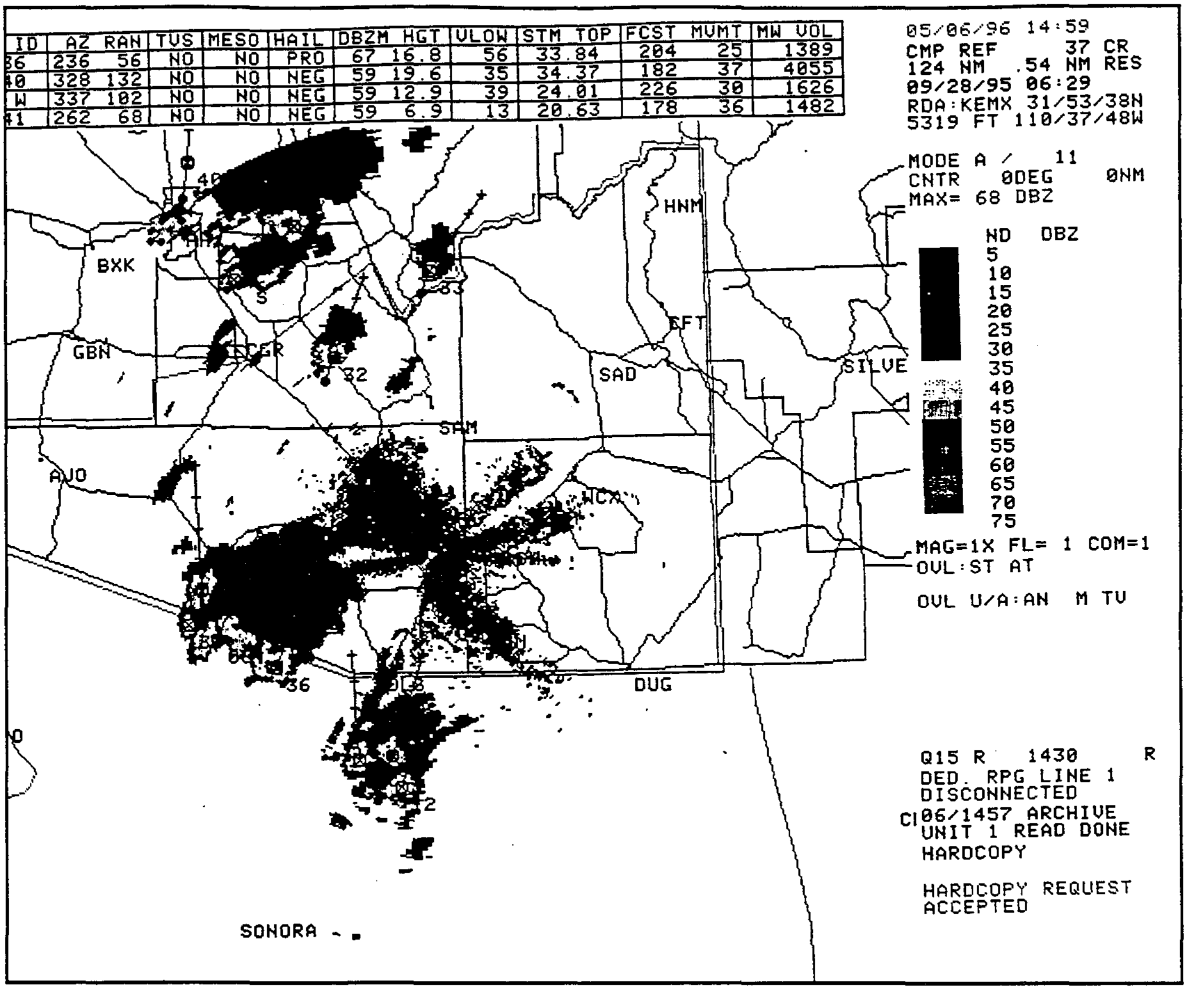


Figure 14b: Cloud-to-ground lightning data from the September 27-28, 1995 splitting supercell thunderstorms between 0515 and 0615 UTC.



ID	AZ RAN	TVS	MESO	HAIL	DBZM HGT	VLOW	STM TOP	FCST MVMT	MW VOL
36	236 56	NO	NO	PRO	67 16.8	56	33.84	204 25	1389
40	328 132	NO	NO	NEG	59 19.6	35	34.37	182 37	4055
W	337 102	NO	NO	NEG	59 12.9	39	24.01	226 30	1626
41	262 68	NO	NO	NEG	59 6.9	13	20.63	178 36	1482

05/06/96 14:59
CMP REF 37 CR
124 NM .54 NM RES
09/28/95 06:29
RDA:KEMX 31/53/38N
5319 FT 110/37/48W

MODE A / 11
CNTR 0DEG 0NM
MAX= 68 DBZ

MAG=1X FL= 1 COM=1
OVL:ST AT
OVL U/A:AN M TV

Q15 R 1430 R
DED. RPG LINE 1
DISCONNECTED
CI 06/1457 ARCHIVE
UNIT 1 READ DONE
HARDCOPY

HARDCOPY REQUEST
ACCEPTED

Figure 15a: Composite reflectivity from KEMX on September 27-28, 1995 at 0629 UTC showing improved coverage of storms as they moved closer to the radar.

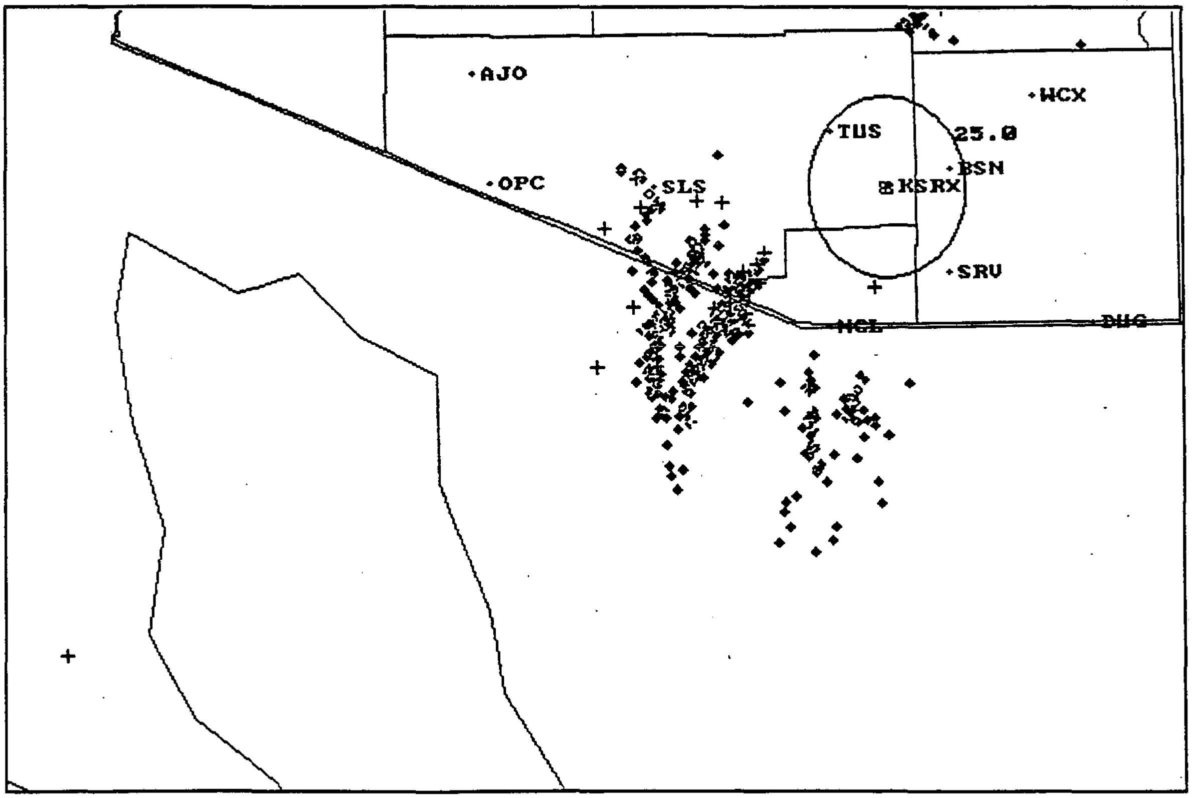


Figure 15b: Cloud-to-ground lightning data from the September 27-28, 1995 splitting supercell thunderstorms between 0515 and 0700 UTC.

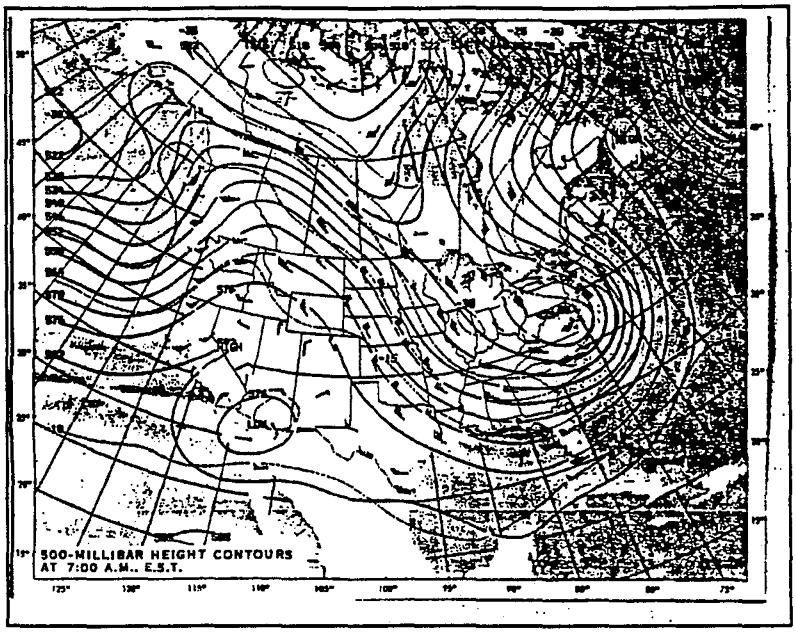


Figure 16: The 500 mb chart for 1200 UTC November 15, 1995 from Daily Weather Summary.

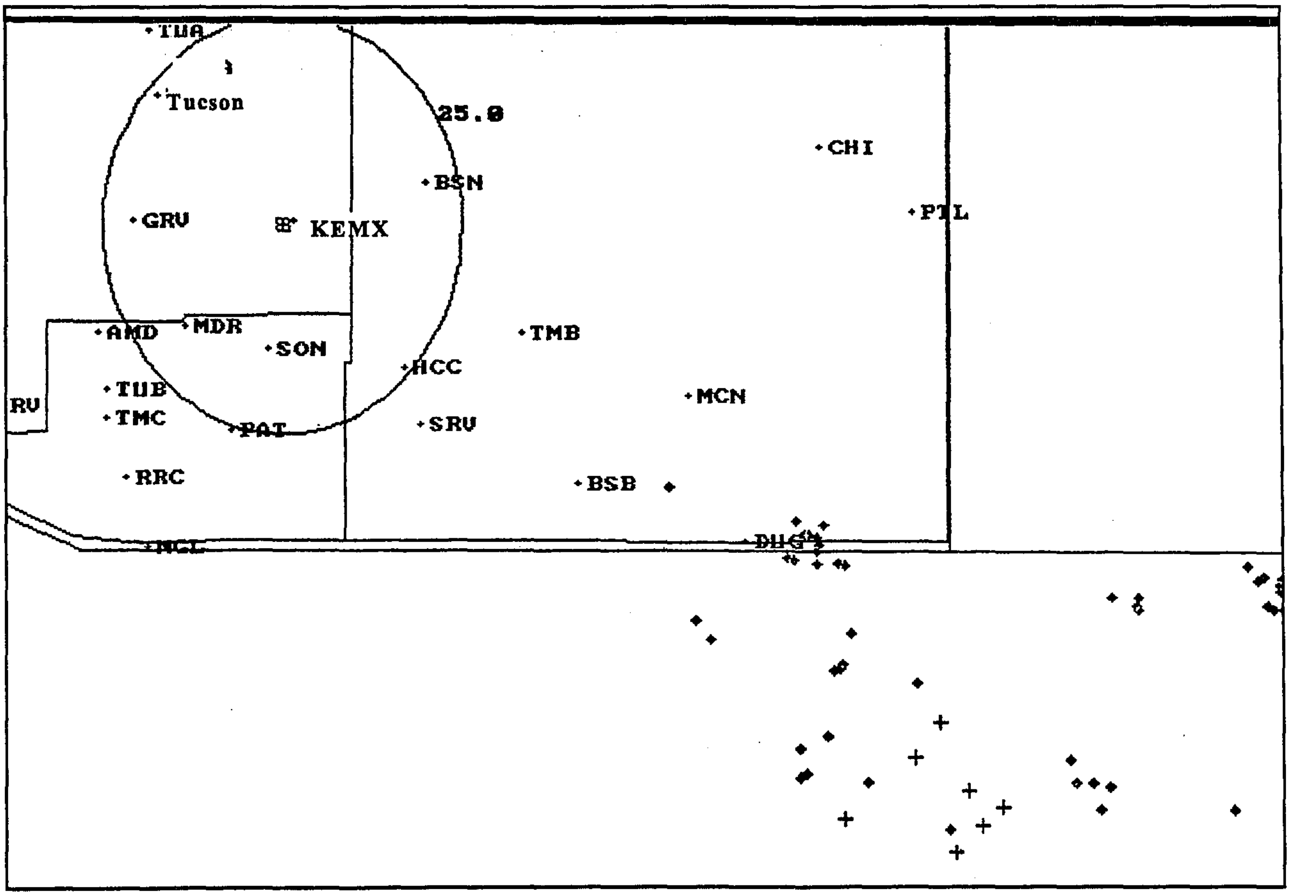


Figure 17: Lighting history for the low topped thunderstorms that occurred on November 15, 1995.

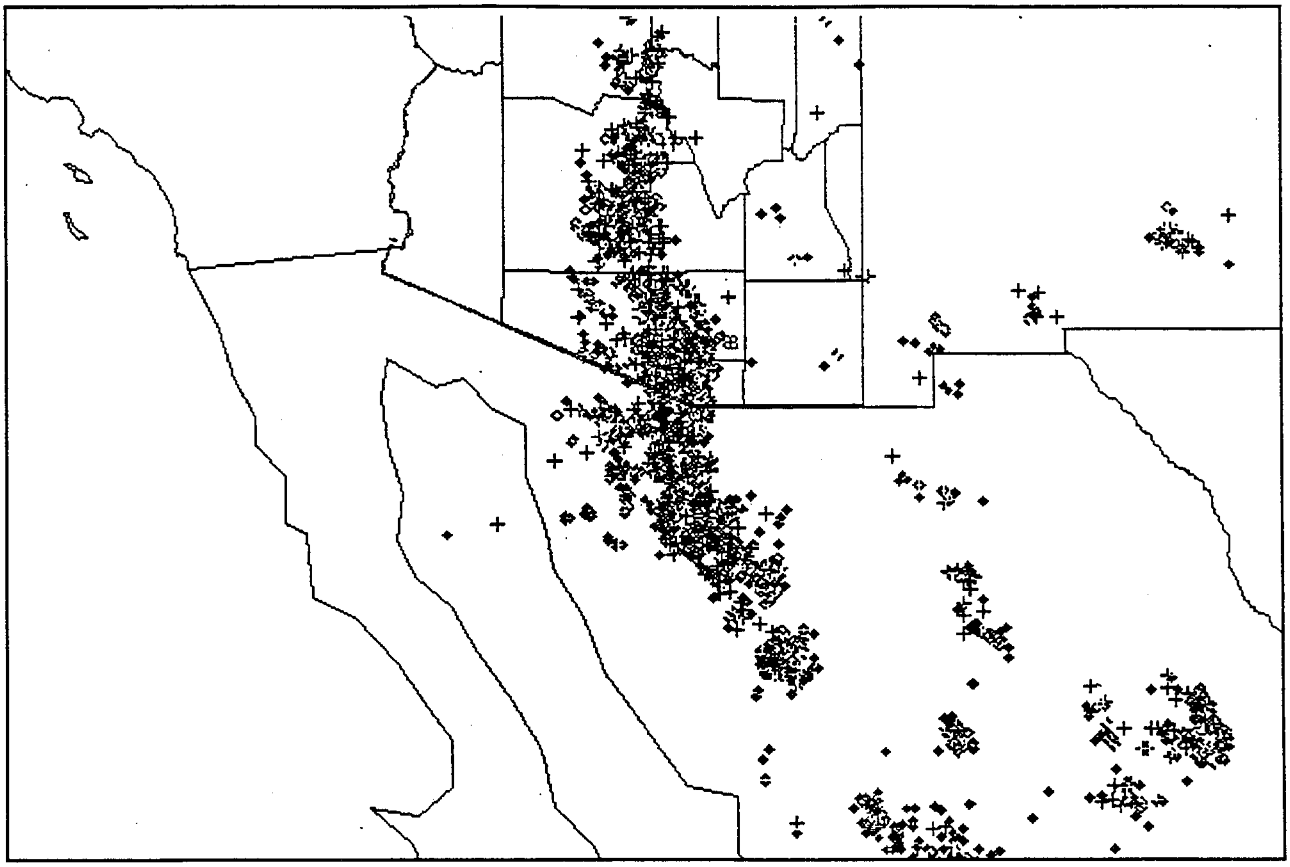


Figure 18: Depiction of NLDN cloud-to-ground lightning data coverage into Mexico.

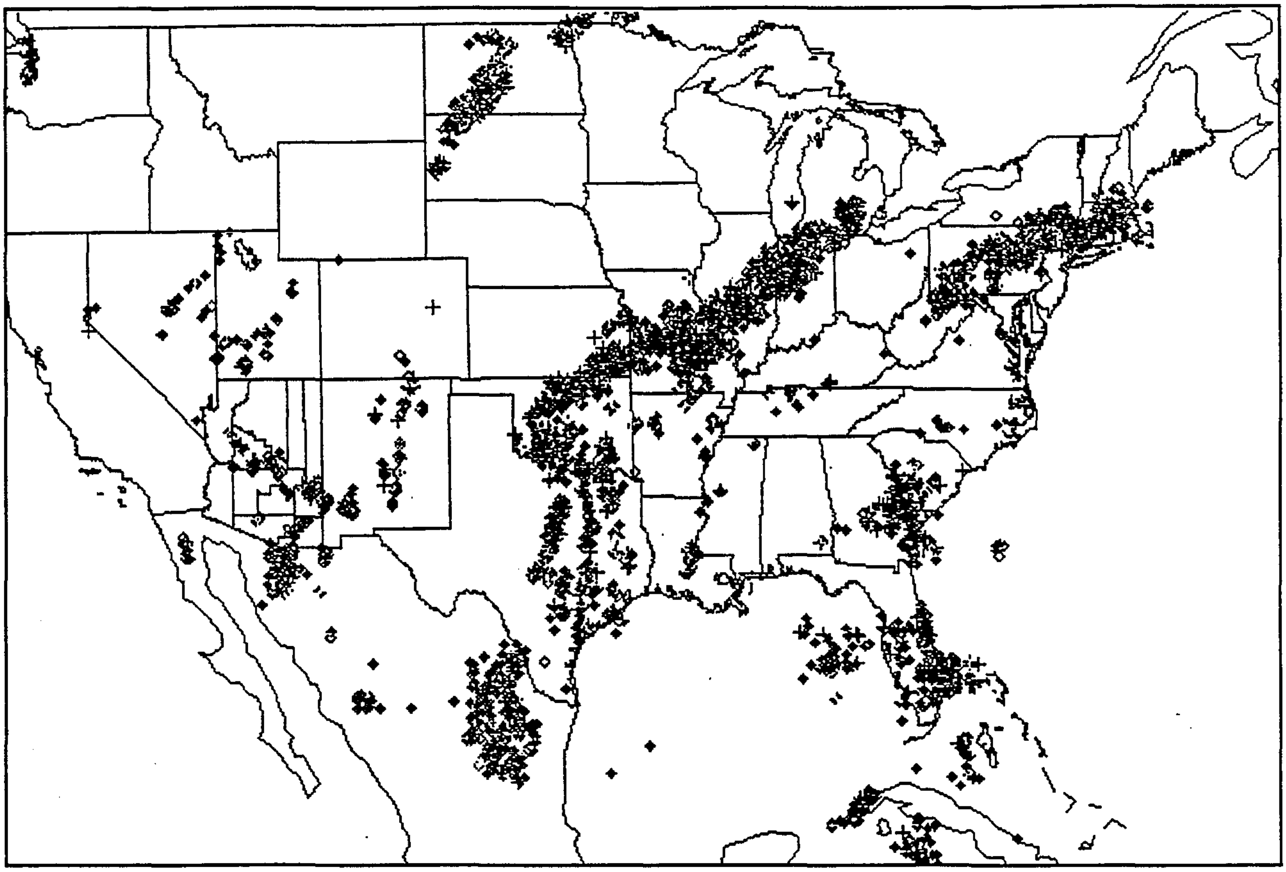


Figure 19a: Depiction of cloud-to-ground lightning data coverage on the national scale. Data depicted is from August 2, 1995.

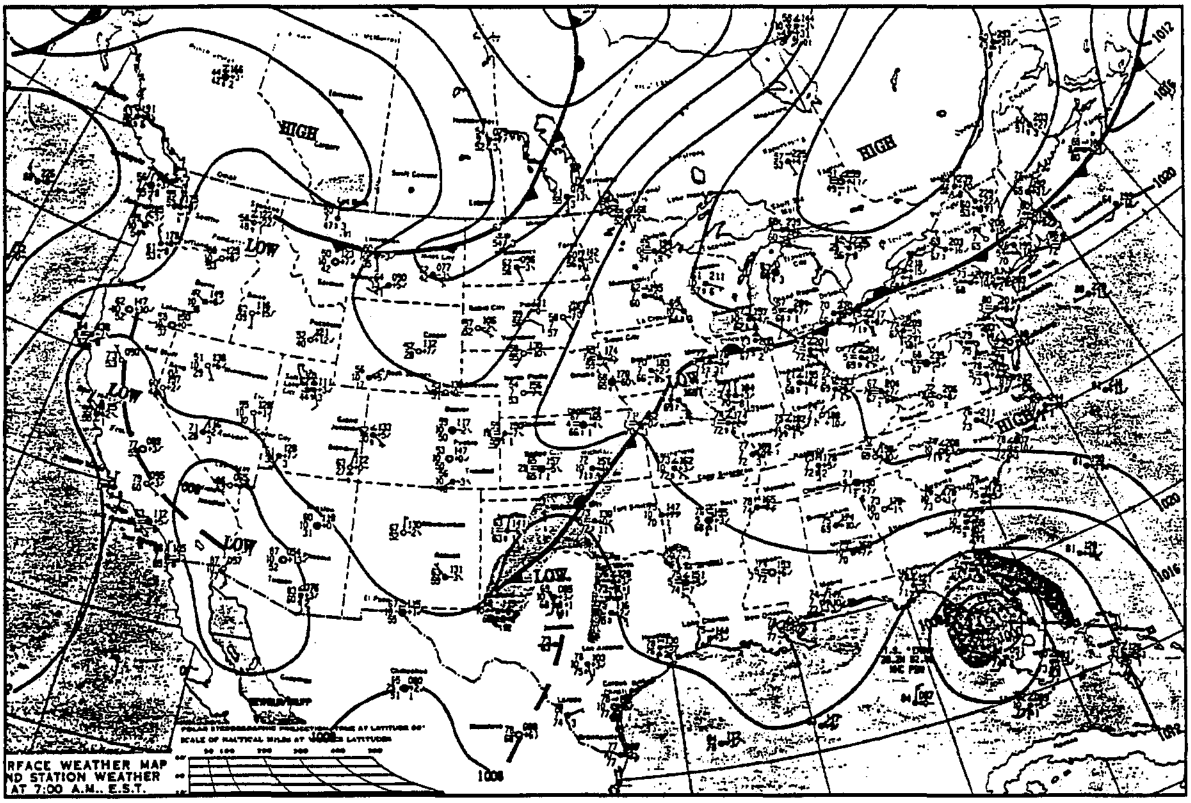


Figure 19b: Surface analysis from Daily Weather Summary for August 2, 1995 at 1200 UTC.

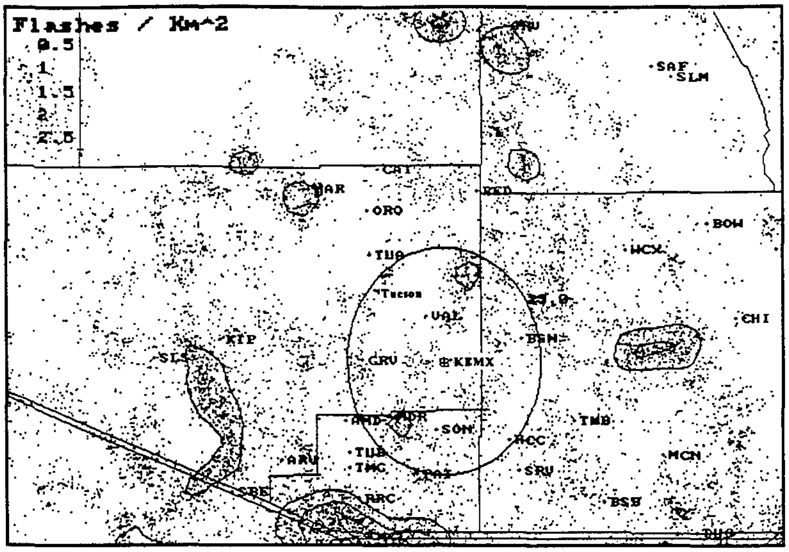


Figure 20a: Composite of cloud-to-ground lightning strikes across southeast Arizona for the period August 1 to August 11, 1995.

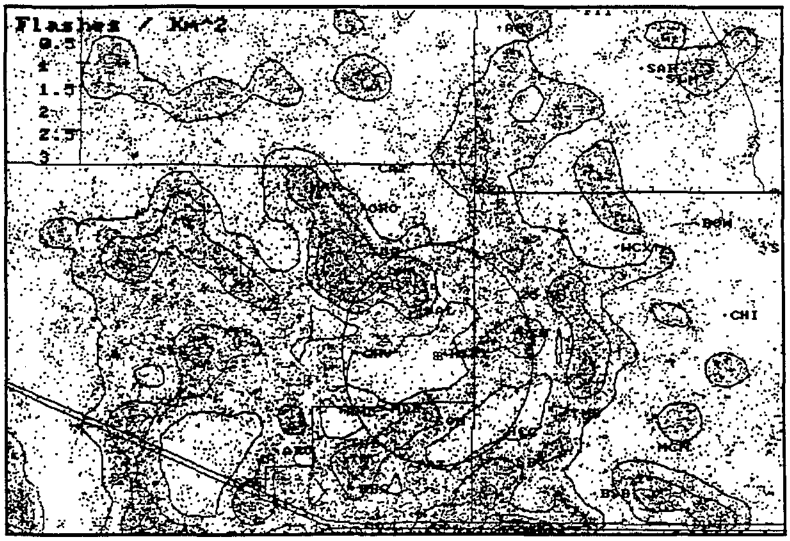


Figure 20b: Same as in (a) except August 11 through August 21, 1995.

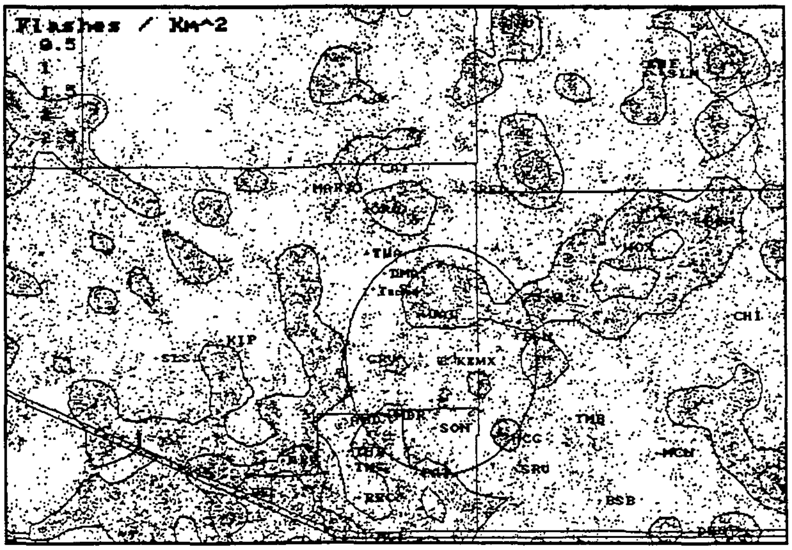


Figure 20c: Same as in (a) except August 21 through September 1, 1995.

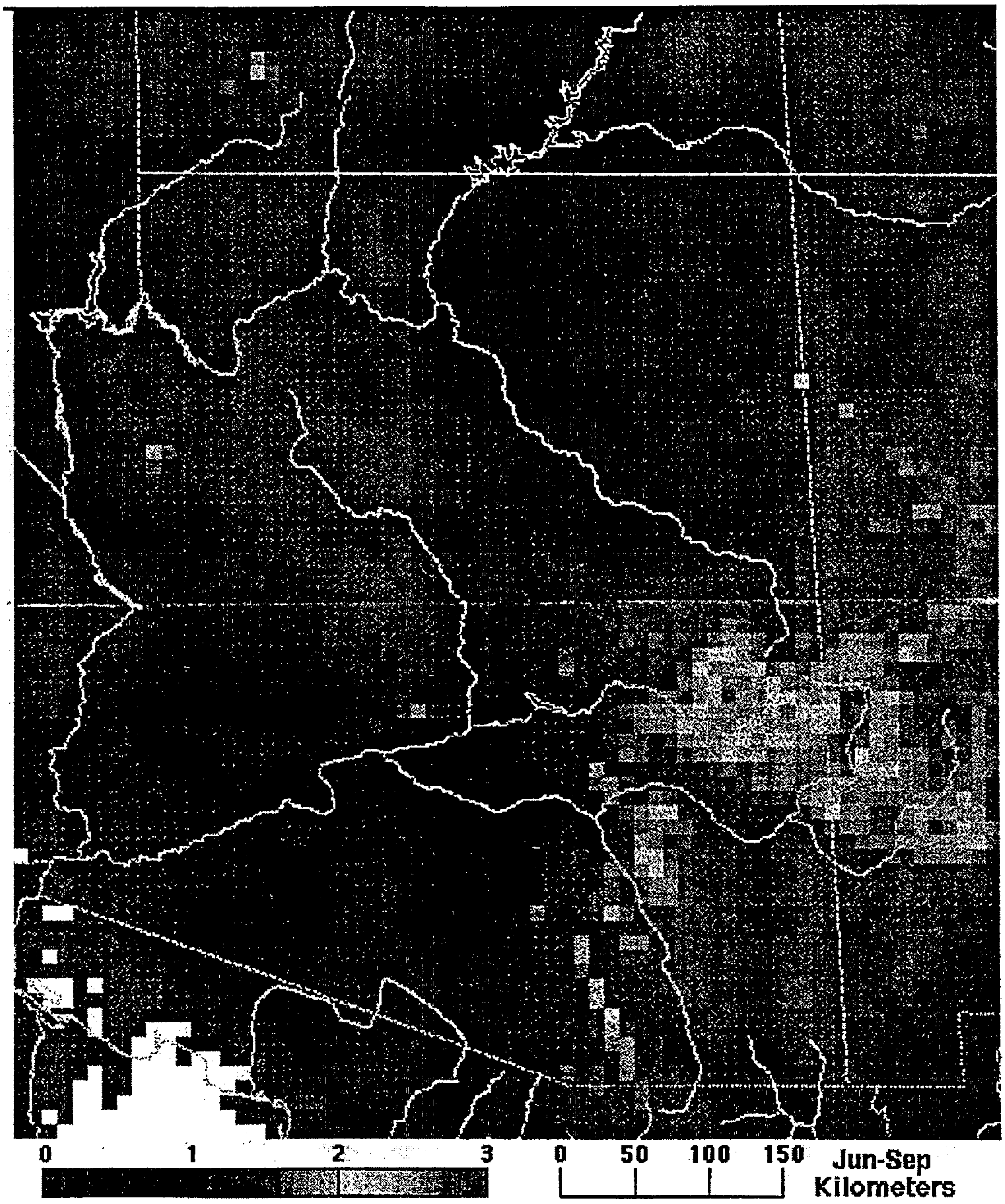


Figure 21: Average number of cloud-to-ground lightning strikes per square kilometer per year for an eight year period (1987-94) for the months of June through September for Arizona (Lopez et al. 1996).

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