CLOUD-TO-GROUND LIGHTNING PATTERNS IN NEW MEXICO DURING THE SUMMER

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Abstract

Six years of Bureau of Land Management (BLM) lightning data were used to investigate the distribution of lightning across New Mexico during the summer. Since lightning indicates the presence of thunderstorms, the BLM database also provided information on the spatial and temporal variations of deep, moist convection in the state.

High cloud-to-ground flash densities were found in most of the mountainous areas, except in some of the higher terrain of the Rocky Mountains over northern New Mexico. The highest flash densities were along an escarpment in the eastern plains which has considerable topographic relief. Low flash densities were in the basins and valleys of the state.

Lightning typically began over the higher terrain near midday and ended over the lowlands at night. Over northeastern New Mexico, maximum lightning activity moved off the eastern slopes of the Sangre de Cristo Mountains during the early afternoon and entered the Tucumcari Basin during the early evening hours. No other area in the state exhibited a similar or organized movement of lightning activity.

1. Introduction

New Mexico has the highest number of mean annual thunderstorm days in the western United States (MacGorman et al. 1984). Moreover, the high plains of the northeastern section of the state average over 70 thunderstorm days each year, which is exceeded only in Florida and along the Gulf Coast. While most of the thunderstorms that occur in New Mexico can be characterized as non-severe, hazards to life and property are not lacking. For example, the state is second in lightning casualties per population density in the United States (Curran et al. 1995).

Since 1976, the Bureau of Land Management (BLM) has been monitoring lightning in the western United States using an array of magnetic direction finders. In this data sparse region of the country, the BLM detection system has aided operational meteorologists in locating thunderstorms for over a decade. In 1983, the BLM began archiving lightning data for the purpose of developing a long-term database for the western United States. Reap (1986) used two years of the BLM lightning dataset to develop a lightning climatology of the western United States

during the summer months. He noted a pronounced increase in lightning activity with elevation in the western U.S.

In this paper, some of the climatological characteristics of lightning in New Mexico during the summer rainy season will be described and analyzed. An important objective is to relate lightning patterns to topography. The study also attempts to document the diurnal variations of lightning activity, and to correlate lightning activity with the geographical variation of rainfall.

2. Data and Analysis

The lightning data consist of the time and location of cloud-to-ground (CG) flashes measured by the BLM lightning detection system for the 1985-1990 summer months (June–September). The BLM system uses magnetic sensors that respond to CG lightning, rather than to cloud-to-cloud discharges and background noise (Krider et al. 1980). The network is comprised of 35 direction-finder (DF) sites in the western United States. Four sites in New Mexico were located near the cities of Albuquerque, Gallup, Roswell, and Socorro (see Fig. 1). Additional sites in Colorado (Monte Vista) and in Arizona (Tucson) contributed to the lightning location solutions.

The location of a CG flash is obtained by measuring the direction of the magnetic field at the time the return-stroke electromagnetic field reaches its initial peak, which is just after the stepped leader contacts the ground (Krider et al. 1980). The CG flash is a lightning discharge to ground and may consist of more than one return strokes. It should be noted that CG lightning accounts for about a one-fourth of all lightning discharges (Pierce 1986).

Estimates of location accuracy and detection efficiency have been made for several lightning detection systems used in the United States. Location errors of the BLM network can be as high as 15 km, depending on flash location. The detection efficiency is probably around 55 to 60% (Watson et al. 1994).

For the purpose of analysis, a grid was placed over the state. All grid cells were of equal area (400 km²), or approximately 20 km on a side. A 20-km grid was selected to encompass the relatively high location error frequency of the BLM network. Individual CG flashes were first located and then placed in the nearest grid cell. Hourly and total flash grids were compiled for the 6 years and then contoured for presentation.

Precipitation data for 1980 to 1990 were obtained from the Hourly Precipitation Data (HPD) archives maintained by the National Climatic Data Center (NCDC) in Asheville, North Carolina and the NOAA Forecast Systems Laboratory in Boulder, Colorado.

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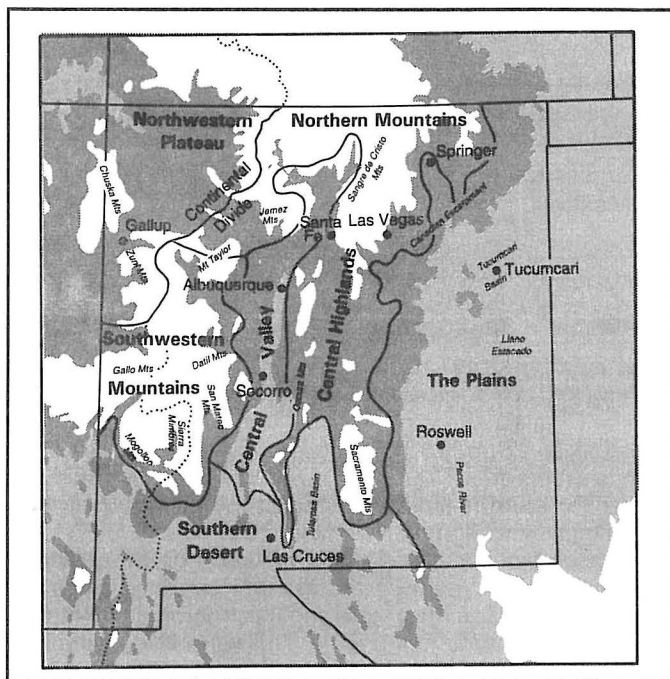
Fig. 1. Map of New Mexico, eastern Arizona, and portions of Utah, Colorado, Texas and Mexico showing topographical features and analysis domain. Elevations from 915 m (3,000 ft) to 1525 m (5,000 ft) are lightly shaded; 1525–2135 m (7,000 ft) are dark shaded; above 2135 m and below 915 m are white. Geographical zones are labeled and outlined.

Fig. 2. Average precipitation (inches) for New Mexico for 1980–90 during the period June–September. Dots indicate cities located in Fig. 1.

3. New Mexico Topography

The topography of New Mexico is diverse and complex. The western two thirds of the state are part of the North American Cordillera, which extends from the Canadian Rocky Mountains to the Mexican Plateau. East of the Cordillera lie the plains of New Mexico, a region with less topographic relief but nonetheless marked by many prominent plateaus and escarpments.

This complex topography exerts a strong influence on the climate of the state, from the planetary scale to the mesoscale. At the large scales, the North American Cordillera creates monsoonal circulation systems which manifest themselves as distinct seasonal climatic features, such as the summer plateau monsoon regime (Tang and Reiter 1984). At the mesoscale, the complex terrain creates thermally driven convergence zones that generate the vast majority of thunderstorms over the state (Hill 1993). Thus, an understanding of the spatial and temporal variations of thunderstorms and lightning should begin with a familiarity of the topography of the state.

Figure 1 depicts the major landforms and related geographic features of New Mexico (Tuan et al. 1973). The seven geographic zones labeled and outlined in Fig. 1 roughly correspond to physiographic divisions, as well as to climatic and NWS forecast zones. Details of the topography to note are:

- The Northern Mountains are composed of the southward extension of the Southern Rockies and include elevations above 10,000 feet (3048 m). The highest mountain in the state, Wheeler Peak, reaches an elevation of 13,160 feet (4011 m).
- The Central Valley, Central Highlands and Southern Desert are the northward extension of the Mexican Plateau. The
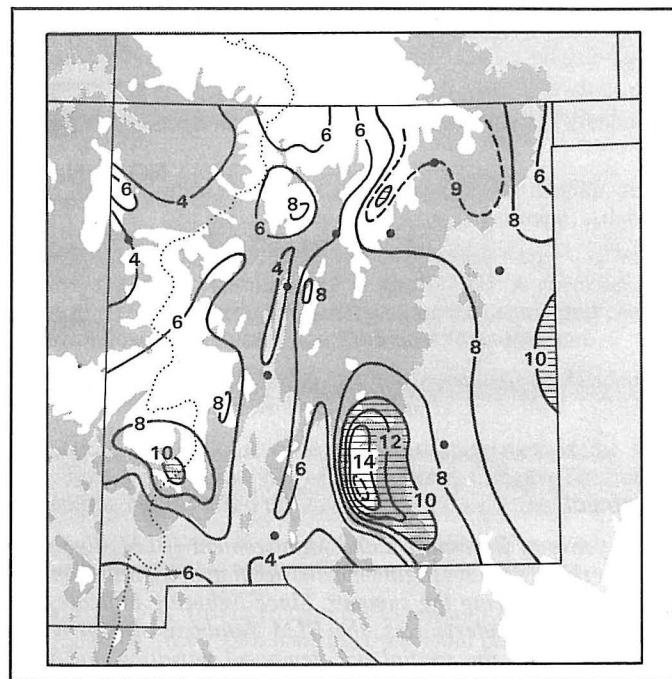
highest point is Sierra Blanca (12,003 ft/3659 m) in the Sacramento Mountains. The Central Valley is part of the Rio Grande Rift Valley.
- The Northwestern Plateau corresponds to the Colorado Plateau, which extends into northern Arizona, southeastern Utah and southwestern Colorado.
- The Southwestern Mountains are a volcanic complex dominated by high tablelands, broad basins, and scattered mountain ranges. The highest peak is Whitewater Baldy (10,892 ft/3320 m) in the Mogollon Mountains.
- The Plains are part of the Great Plains Province. The northern section consists of piedmont plains and high plateaus cut by numerous rivers; the southern section includes tablelands and broad lowland plains.
- The Continental Divide winds along the eastern boundary of the Northwestern Plateau and through the Southwestern Mountains and Southern Desert.

4. Summer Rainy Season

Throughout most of New Mexico, the majority of precipitation falls during the summer rainy season. Over the eastern plains the rainy season begins in May and continues through October. In the western two thirds of the state, the wet season is delayed until late June and July and ends gradually in September (Tuan et al. 1973).

Figure 2 shows a hand analysis of the average precipitation amounts for the period June through September from approximately 50 HPD stations across the state of New Mexico. Sites receiving 8 inches or more are located in the major mountains of the state and throughout most of the Plains. Lesser amounts
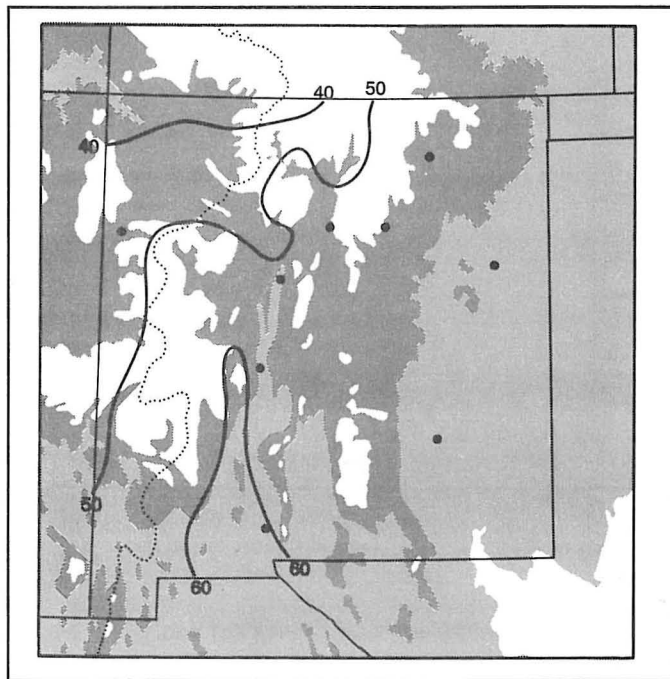
Fig. 3. Percent of annual precipitation during June–September.

Fig. 4. Total negative CG flash densities (flashes per 100 km² per summer) for 20 × 20-km grid cells during all hours for 1985–1990.

of four inches or less are found over the Northwest Plateau and Central Valley.

Most of the state receives from 50 to 60% of its annual precipitation from June through September, except for northwestern New Mexico, which receives less than 50% (Fig. 3). This occurs because the Northwest Plateau is situated on the western side of the Continental Divide and, therefore, receives a substantial portion of its yearly precipitation during the winter from extratropical cyclones originating over the Pacific Ocean.

Precipitation occurring over the Plains during June is due mainly to frontal passages and upper air disturbances moving out of the central and southern Rocky Mountains (Webb 1992). By late June or early July the westerlies shift poleward and the subtropical ridge expands north and westward over North America, allowing subtropical moisture to enter the state from the Gulf of Mexico, Gulf of California and eastern Pacific. The dramatic increase in moisture and precipitation in July over the western half of the state is the summer monsoon. The greatest monthly precipitation amounts occur during the monsoon months of July and August throughout New Mexico.

By mid-September the monsoon has typically ended. However, tropical cyclones and their remnants often produce significant rainfall from late August through September (Webb 1992).

5. Lightning Patterns In New Mexico

Figure 4 shows the average CG flashes during the summer months. The highest flash densities are in the Plains, Central Highlands, and Northern and Southwestern Mountains, with the axis of maximum values extending westward into the White Mountains of Arizona. Low flash densities occur over the Northwest Plateau, Central Valley, and Southern Desert.

These results are significantly different from those found by Reap (1986). In his two-year lightning climatology of the west-
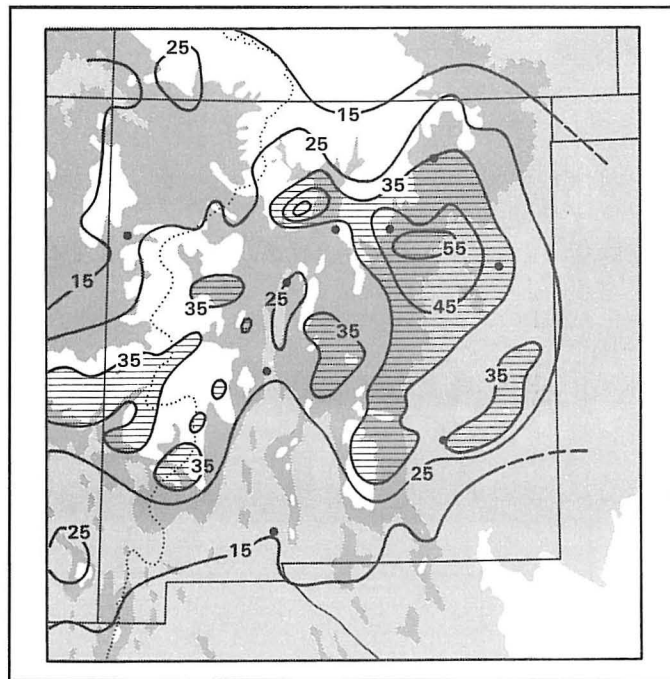
ern United States during the summer months, he placed the primary maximum of lightning strikes over the Northwest Plateau (see his Fig. 10). However, he states that heavy lightning activity in that region is not easily explained. His study used a 48 × 48-km grid, compared to the 20 × 20-km grid used in this study, and included lightning data for only two summers. Thus, the results may not be comparable.

Comparison of Fig. 4 with the 1989 National Lightning Detection Network flash density map (Orville 1991) reveals a potential problem with the BLM lightning network over eastern New Mexico. The BLM network alone showed a pronounced decrease in flash density from the maximum located southeast of Las Vegas to the New Mexico/Texas border, while the national network showed little, if any, decrease over this same region. The rapid decrease in flash density over the eastern plains was likely due to the fact that the BLM network ends there, resulting in a significant decrease in the detection efficiency over the extreme eastern section of the state, while Orville's data link with antennas to the east not in the BLM network.

In Fig. 4 the complex relationship between lightning activity and topography in New Mexico is clearly evident. Over much of the state, high flash densities correlate closely with the elevated terrain found in the mountainous areas, such as the Southwestern Mountains, portions of the Northern Mountains, and the Sacramento Mountains of the Central Highlands. An excellent example of the strong correspondence between high flash densities and elevated terrain was the high lightning activity (55 flashes per 100 km² or more) directly over the Jemez Mountains, which are comprised of isolated peaks rising over 11,000 feet (3353 m).

However, unlike many of the local lightning maxima, the area having the greatest flash densities in New Mexico cannot be characterized as mountainous. This area was between Las Vegas and Tucumcari in the Plains and was directly over the southern portion of the Canadian Escarpment, a 50 mile long
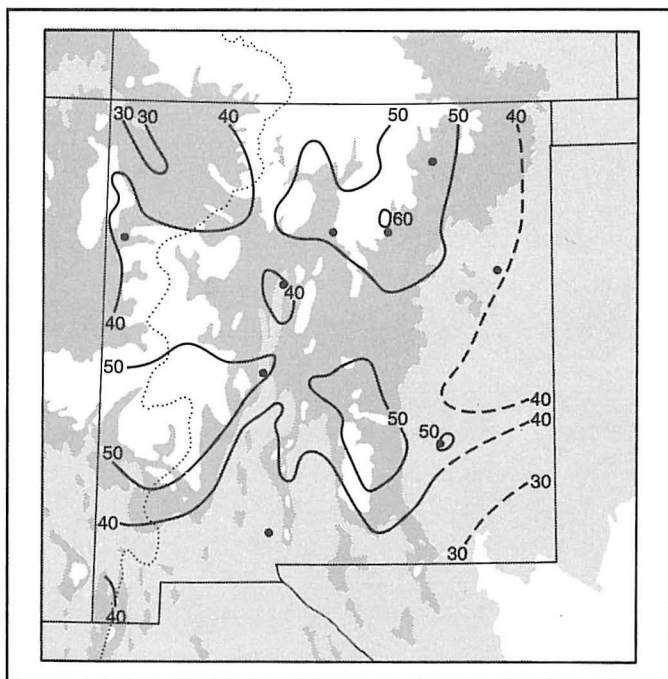
Fig. 5. Thunderstorm days (two or more CG flashes in each 20 × 20-km grid cell per day) per summer for 1985–1990.

Fig. 6. Average hourly variation of CG flashes across New Mexico during the summer for 1985–1990.

cliff that rises nearly 1,000 feet above the lowlands to the south with slopes facing south and southeast. The location of this maximum is consistent with the pattern of lightning activity over northeastern Colorado where lightning was found preferentially over the slopes of mountains and ridges facing the low-level moisture flow and not over the highest terrain elevation (López and Holle 1986).

The lowest flash densities are over the basins and valleys, such as the Rio Grande Valley, the Northwest Plateau, and Southern Desert. The low flash density over the extreme southeast corner of the state is suspected to be too weak because the region is beyond the range of the BLM lightning detection network.

The area of low flash densities of less than 25 flashes per 100 km² found over the northern half of New Mexico is interesting because it includes some of the highest terrain in the state. This low flash density area is inconsistent with the pronounced increase in lightning activity with elevation over the western United States found by Reap (1986).

While Fig. 4 identifies those areas having the greatest flash densities and, therefore, posing the greatest threat to public safety, it does not provide information on the characteristics of the thunderstorms that produced the high densities, such as thunderstorm frequency, duration, and flash rates. For example, the high flash densities over the Canadian Escarpment may have resulted from a high frequency of thunderstorms or from a few thunderstorms having very high flash rates.

To provide additional insights into the lightning climatology of New Mexico, maps of the frequency of two or more lightning flashes per day for each 20 × 20-km grid cell were produced to show the daily distributions of thunderstorms across the state (Fig. 5). The resulting map reveals a great deal about the geographical distribution of thunderstorms, regardless of their flash rates or intensities, even though it may underestimate
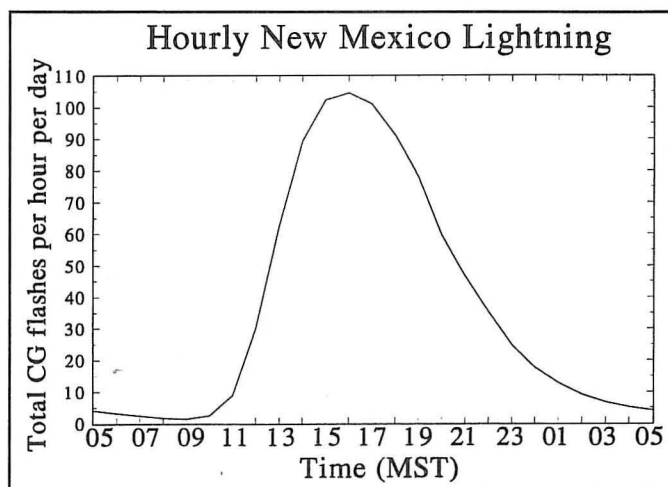
the total number of distinct thunderstorms occurring in each grid cell.

There is a remarkable correspondence between Fig. 5 and the map of mean annual thunderstorm days as determined by surface observations given by MacGorman et al. (1984), except over the extreme eastern section of the state where the instrument attenuation problems were evident again. Both maps show maximum thunderstorm days over the northern section of the Plains, with values exceeding 60 days near Las Vegas. Moreover, the low number of thunderstorm days (less than 30) over the Northwest Plateau is evident in both maps.

The relationship between thunderstorm days and topography appears more straightforward than that between CG flash densities and topography. Areas with more than 50 thunderstorm days occurred almost exclusively over the higher terrain, whereas those areas having less than 40 thunderstorm days were over the major basins and valleys. In addition, high flash densities in Fig. 4, along with a large number of thunderstorm days (Fig. 5), suggest a growth region along the Canadian Escarpment in northeast New Mexico. Apparently, due to a supply of available moisture, the activity persists as it moves eastward out into the Plains.

In contrast, in the Northern Mountains and along the New Mexico-Colorado border, there are relatively low flash densities coupled with a high number of thunderstorm days. This would indicate a region where the convective activity is probably in the decay stage.

6. Diurnal Lightning Patterns

The hourly variation of total CG flashes in New Mexico during the 1985–90 summer months is shown in Fig. 6. The diurnal lightning pattern was similar to that of the western United States (Reap 1986), northeastern Colorado (López and Holle 1986), and Arizona (Watson et al. 1994) during the summer. It shows a rapid rise in total CG flashes from the minimum at 0900 MST (1600 UTC) to the maximum at 1600 MST (2300 UTC), then a steady decrease through midnight.

To describe the hourly variation of lightning activity across New Mexico, selected hourly flash maps were constructed. For presentation purposes, maps are given every three hours from midday to near midnight.
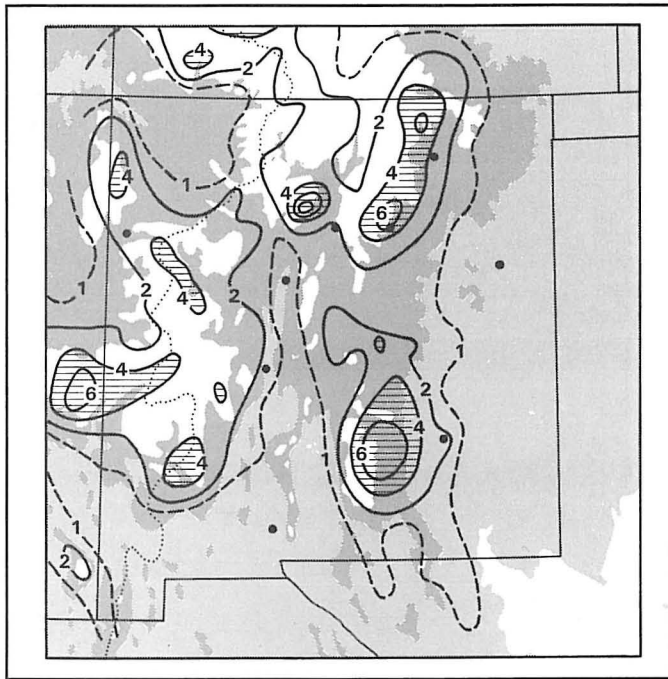
Fig. 7. CG flash densities (flashes per 100 km² per summer) for the 1-h period ending at 1300 MST (2000 UTC) for 1985–1990.

Fig. 8. Same as Fig. 7 except for 1600 MST (2300 UTC).

Figure 7 is the flash map for 1300 MST (2000 UTC) and clearly shows the strong influence of elevated terrain on the generation of strong convection. The areas having the greatest activity were over the eastern slopes of major orographic features such as the Sacramento, Sangre de Cristo and Jemez Mountains. Other areas of significant activity were directly over prominent mountain ranges such as the Chuska, Zuni, Gallo, San Mateo and Mimbres Mountains. The high flash densities over the eastern slopes of the Sangre de Cristo Mountains near midday coincide with one of the major thunderstorm "genesis zones" over northern New Mexico and Colorado, which were identified by Banta and Schaaf (1987) using GOES satellite images. They noted that this genesis zone was most active when mid-level flow was northwesterly, suggesting that convection was initiated as a result of the convergence of thermally-forced upslope flow and the opposing ridgetop winds. It is plausible that this leeside convergence mechanism was also responsible for the high lightning activity found over the eastern slopes of the other mountains mentioned above.

Figure 8 shows the pattern of CG flash densities at 1600 MST (2300 UTC), the time of peak activity over the state. Increases in CG flashes from 1300 MST occurred over the Southwestern Mountains, Central Highlands and the Plains. The greatest activity was over the Mogollon Mountains of the Southwest Mountains, near the Oscura Mountains in the Central Highlands, and the Canadian Escarpment. Significant decreases were noted over the Jemez and Sacramento Mountains.

Lightning activity decreased significantly over most of the state into the early evening hours (Fig. 9), especially over the Southwest Mountains and the plains north of the Canadian Escarpment. In contrast, increases occurred over the Tucumcari Basin in the Plains.

The final flash map (Fig. 10) shows that lightning activity continued to decrease over most of the state into the night, except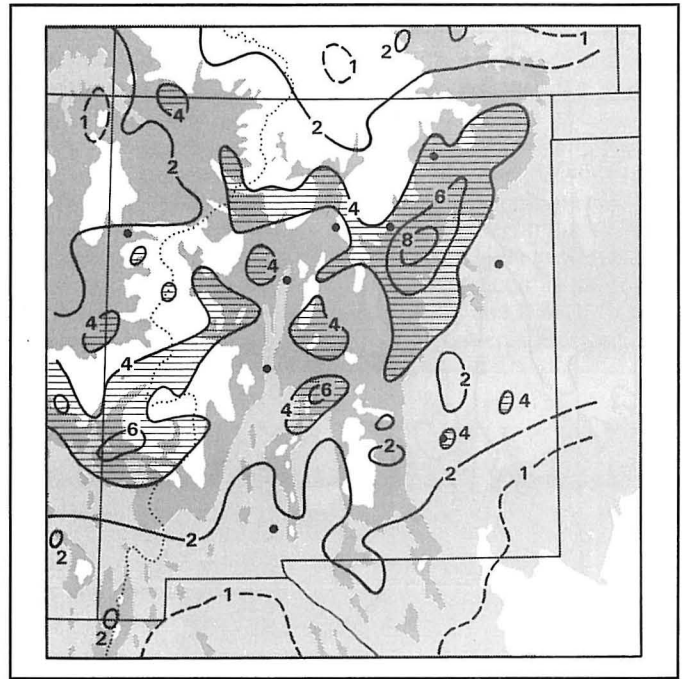 for the notable increases over the Llano Estacado in eastern New Mexico. The areas with the greatest flash densities (greater than one CG flash per 100 km²) were over the Plains, Southern Desert and Central Valley which include some of the lowest terrain in the state. Over the Tularosa Basin several grid cells had primary or secondary maxima in flash densities during the early nighttime hours. This corroborates the findings of Tucker (1993) who showed either a primary or a secondary maximum in the frequency of hourly precipitation events (> 0.1 inches or 2.54 mm) within two hours of midnight for eight stations in south-central New Mexico.

The nocturnal lightning activity maxima over the Southern Desert and the Plains shown in Fig. 10 closely matches the axis of the maximum occurrence of "late" (near midnight) thunderstorms (Wallace 1975 and Fig. 4 in Reiter and Tang 1984). Reiter and Tang (1984) argue that the development of nocturnal convection around the edges of the elevated terrain of the North American Cordillera in the United States (the U.S. Western Plateau) is a result of the large-scale monsoonal circulation induced by the integrated effects of the heat balance over the plateau.

As shown above, the diurnal variability of CG flash density over New Mexico was highly dependent on topography and the daily solar heating cycle. Maximum lightning activity occurred over the mountainous areas during the early afternoon hours and then over the lowlands of the southern and eastern sections of the state during the early evening and nighttime hours. A similar diurnal pattern in CG flash densities has been reported by Watson et al. (1994) in Arizona during the monsoon.

A map of the isochrones of the axis of maximum CG flashes during the period from 1200 to 2400 MST (1900 to 0700 UTC) was created to study the movement of CG lightning in the state (Fig. 11). Not surprisingly, many of the isochrones were over the major orographic features of New Mexico. The displacement of consecutive isochrones over most of the state showed no coherent pattern, except in the Plains.
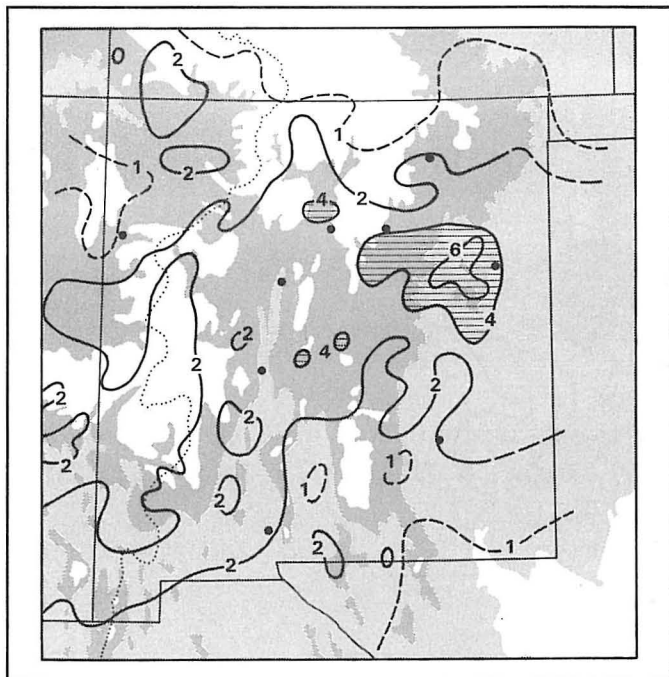
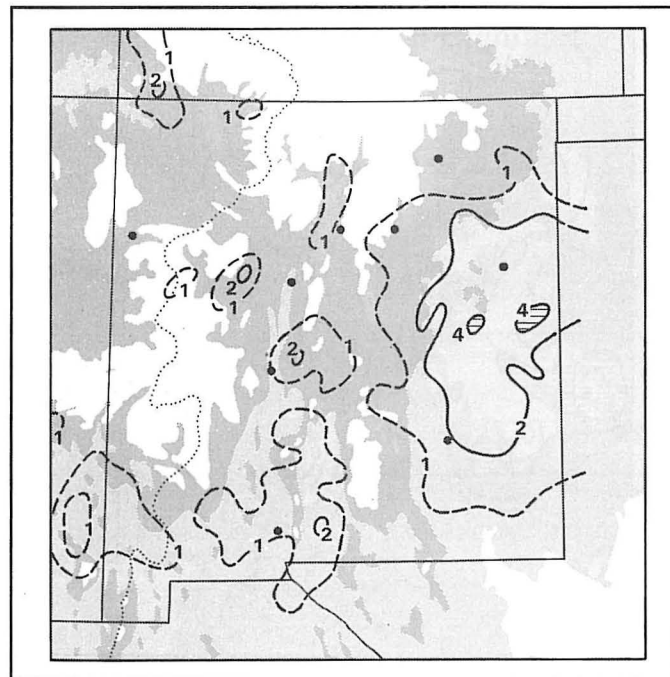Fig. 9. Same as Fig. 7 except for 1900 MST (0200 UTC).

Fig. 10. Same as Fig. 7 except for 2200 MST (0500 UTC).

During the 6-hour period beginning with the 1200 MST flash maximum over the eastern slopes of the Sangre de Cristo Mountains, the axis of maximum lightning activity moved southeastward across the plains of northeastern New Mexico to the Tucumcari Basin (Fig. 11). Thereafter, the continuity of consecutive flash maxima was obscured by axes from other maxima over eastern New Mexico. However, a sequence of consecutive flash maxima was discernable beginning with the 1800 MST flash maximum over the Tucumcari Basin and ending with the maximum over the Llano Estacado at 2400 MST. Over the 12-hour period, the average rate of displacement of the isochrones of maximum lightning was 5.8 m s^{-1}, which is similar to results from a study of the movement of radar echoes of thunderstorms off the higher terrain of southeast Colorado (Karr and Wooten 1976) during the summer.

The southeastward movement of the CG flash maxima across the Plains may be due to the fact that the frequency of thunderstorm genesis along the eastern slopes of the Sangre de Cristo Mountains is greatest during mid-level northwest flow, as mentioned above. Thus, along with enhancing leeside convergence, mid-level northwest flow may be steering the mountain-generated thunderstorms southeastward across the Plains later in the day.

The movement of maximum hourly flash densities over the Plains described above may not have represented average CG lightning patterns over that part of the state. Instead, it may have represented a few convective systems that were associated with very high flash densities. To underscore this, Goodman and MacGorman (1986) found that a single mesoscale convective complex (MCC) can contribute up to 25% of the ground flashes annually.

7. Lightning and Precipitation Relationships

Observational studies relating lightning to precipitation include Watson et al. (1994), who showed that precipitation

related well with CG flash densities in Arizona. Ellison (1992) investigated the relation between rainfall rates and lightning intensity of a mesoscale convective system over the Southern Desert of New Mexico and observed that heavy rain began at the time of peak lightning activity.

Comparisons between lightning activity and precipitation for Albuquerque (Fig. 12) show that both the frequency of significant precipitation (> 0.1 inches per hour) and CG lightning activity increased rapidly after the morning minima to a peak at 1800 MST (0100 UTC). Thereafter, the correlation decreased. The secondary peak in hourly precipitation events at 2200 MST (0500 UTC) was probably due to stratiform precipitation from dissipated thunderstorms with little lightning activity.

The relationship between lightning and precipitation is further complicated by the fact that in the western United States lightning activity often accompanies high-based thunderstorms. Precipitation from such thunderstorms often evaporates, either completely or partially, before reaching the ground.

8. Summary and Conclusions

Analysis of the long-term BLM lightning database has revealed the complex relationship between CG lightning activity and topography in New Mexico during the summer rainy season. It was shown that the highest flash densities were located along the south-facing Canadian Escarpment in the Plains, rather than in elevated terrain found in the mountainous areas of the state. This suggests that terrain features, such as slope and aspect, play a more critical role in the development of deep convection than elevation alone.

Typically, lightning activity began in the mountainous areas near midday and ended in the lowlands near midnight. Peak lightning activity over the entire state occurred at 1600 MST and coincided with maximum hourly flash densities over the Canadian Escarpment.
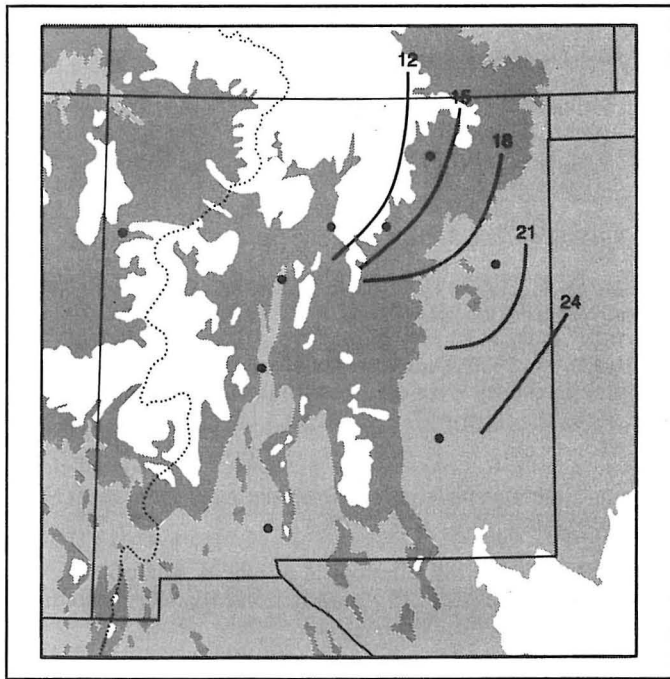
Fig. 11. Selected isochrones of maximum lightning activity over eastern New Mexico for 1200–2400 MST (1900-0700 UTC) in 3-h increments.
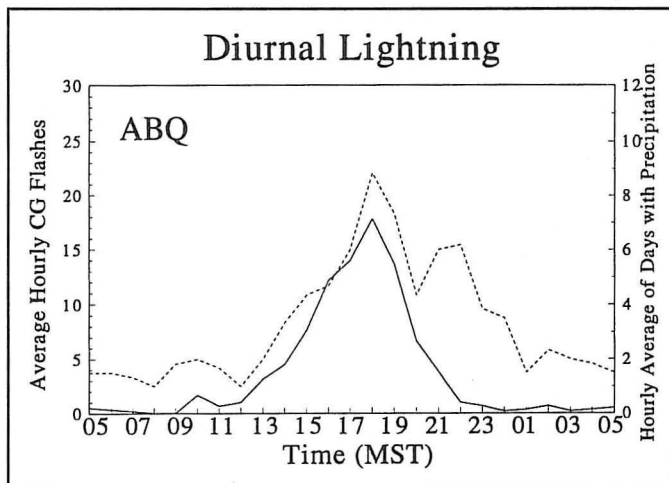

Fig. 12. Average hourly variations of CG flashes (solid) and hourly average of days with significant precipitation (> 0.1 in.) events (dashed) for Albuquerque during the summer.

Many areas exhibiting the first significant lightning activity of the day were along the eastern slopes of major mountain ranges. The high flash densities over the eastern slopes of the Sangre de Cristo Mountains were located in a major thunderstorm genesis zone of the Rocky Mountains, which had been identified earlier by investigators using GOES satellite imagery (Banta and Schaaf 1987). These studies showed that the activation of different genesis zones depends on the direction of the mid-level wind and, therefore, may be predictable.

The high flash densities over the Llano Estacado at 2200 MST (0500 UTC) appear to have resulted from the southeastward

movement of thunderstorms that had formed earlier in the day over the Sangre de Cristo Mountains. A similar pattern was evident in Arizona where thunderstorms (Watson et al. 1994), which formed over the elevated terrain of central and eastern Arizona during midday, moved south and west and entered the lower deserts of southern Arizona by early evening. Other areas in New Mexico that had significant nocturnal lightning activity, such as the Tularosa Basin, did not show lightning activity moving off the surrounding higher terrain and into the lowlands. However, the use of analytical techniques, such as harmonic analysis of the hourly CG flash data (King and Balling 1994), may reveal such movement in lightning patterns elsewhere in the state.

Acknowledgments

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