Intense Convective Storms with Little or No Lightning over Central Arizona: A Case of Inadvertent Weather Modification?

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ABSTRACT

On 20/21 August 1993, deep convective storms occurred across much of Arizona, except for the southwestern quarter of the state. Several storms were quite severe, producing downbursts and extensive wind damage in the greater Phoenix area during the late afternoon and evening. The most severe convective storms occurred from 0000 to 0230 UTC 21 August and were noteworthy in that, except for the first reported severe thunderstorm, there was almost no cloud-to-ground (CG) lightning observed during their life cycles. Other intense storms on this day, particularly early storms to the south of Phoenix and those occurring over mountainous terrain to the north and east of Phoenix, were prolific producers of CG lightning. Radar data for an 8-h period (2000 UTC 20 August–0400 UTC 21 August) indicated that 88 convective cells having maximum reflectivities greater than 55 dB*Z* and persisting longer than 25 min occurred within a 200-km range of Phoenix. Of these cells, 30 were identified as ''low-lightning'' storms, that is, cells having three or fewer detected CG strikes during their entire radar-detected life cycle. The region within which the low-lightning storms were occurring spread to the north and east during the analysis period.

Examination of the reflectivity structure of the storms using operational Doppler radar data from Phoenix, and of the supportive environment using upper-air sounding data taken at Luke Air Force Base just northwest of Phoenix, revealed no apparent physical reasons for the distinct difference in observed cloud-to-ground lightning character between the storms in and to the west of the immediate Phoenix area versus those to the north, east, and south. However, the radar data do reveal that several extensive clouds of chaff initiated over flight-restricted military ranges to the southwest of Phoenix. The prevailing flow advected the chaff clouds to the north and east. Convective storms that occurred in the area likely affected by the dispersing chaff clouds were characterized by little or no CG lightning.

Field studies in the 1970s demonstrated that chaff injected into building thunderstorms markedly decreased CG lightning strikes. There are no data available regarding either the in-cloud lightning character of storms on this day or the technical specifications of the chaff being used in military aircraft anti–electronic warfare systems. However, it is hypothesized that this case of severe, but low-lightning, convective storms resulted from inadvertent lightning suppression over south-central Arizona due to an extended period of numerous chaff releases over the military ranges.

1. Introduction

Cloud-to-ground (CG) lightning strikes detected by the National Lightning Detection Network (NLDN) on 20/21 August 1993 indicate that widespread thunderstorms occurred over north-central and eastern Arizona [the area of interest in this study is within a 200-km radius of the National Weather Service (NWS) radar at Phoenix (located at point ''KIWA'') and is shown in Fig. 1]. Nearly 15 000 CG (note that all references to ''lightning'' in this paper are to detected CG lightning strikes) strikes were detected within this region (see Fig. 2) during the 24 h ending at 1200 UTC 21 August, but few or no lightning strikes were detected over south-central and southwest Arizona. This would normally indicate that deep convective storms did not occur over this portion of the state.

However, in addition to the thunderstorms that produced the detected CG flashes, radar data indicate that many convective cells occurred over south-central Arizona (i.e., eastern Maricopa and all of Pinal Counties; see Fig. 1). At least five intense convective storms developed and quickly became severe as they moved toward or across the greater Phoenix metropolitan area during the late afternoon and evening (i.e., from 0000 to 0230 UTC). The significant convective storms moving across Phoenix did not produce detected lightning activity at rates comparable to those occurring over the higher terrain to the east. In fact, further analysis revealed that several of the deep convective storms oc-

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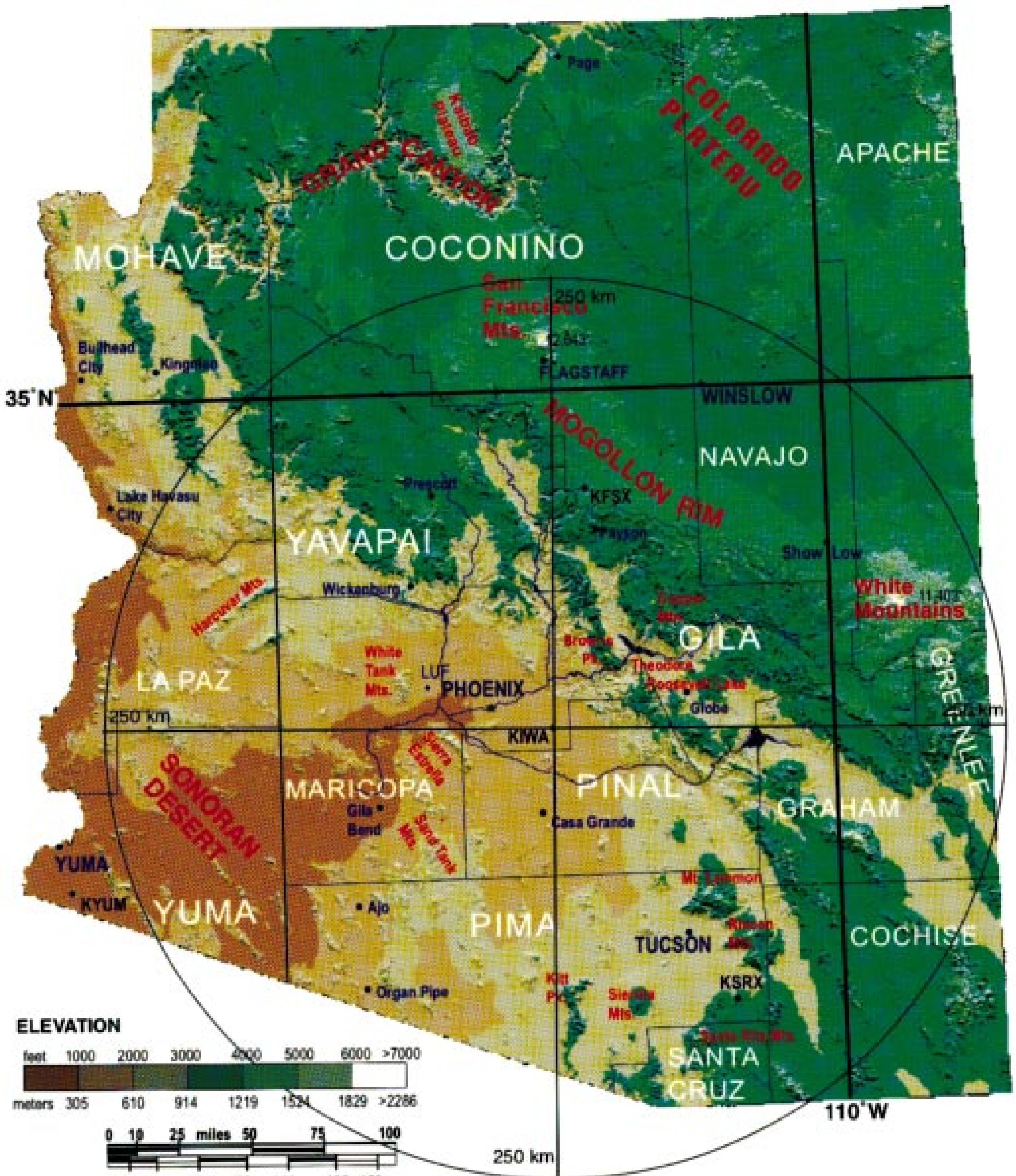


FIG. 1. Map of Arizona showing counties, terrain, and key features or locations referred to in the text.

curring over south-central Arizona (i.e., over Maricopa and western and extreme northern Pinal Counties; again, refer to Fig. 1) produced no detected CG lightning strikes. In western Pinal County some storms were prolific lightning producers before about 0100 UTC (e.g., the first severe storm of the afternoon occurring west of Casa Grande shortly after 0000 UTC), but subsequent storms in the same area produced little lightning.

The reasons for the dramatically different CG lightning strike character of storms that were relatively close together in space and time were not obvious after an initial scan of the data available for this day. This paper reports results of an after-the-fact analysis of this un-

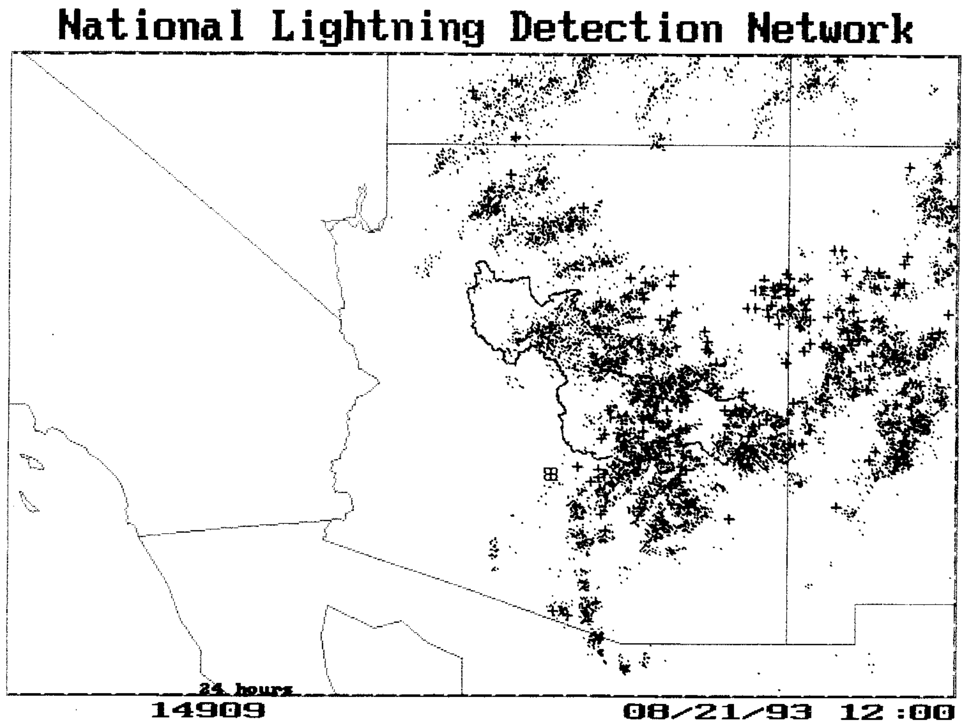


FIG. 2. Cloud-to-ground lightning strikes detected by the National Lightning Detection Network during the 24 hending at 1200 UTC 21 August 1993.

usual event that considered all the relevant meteorological data available.

2. Case analysis

a. Data and observations available

Full-resolution reflectivity data from the Phoenix, Arizona, National Weather Service Doppler weather surveillance radar (i.e., the WSR-88D archive level II data) were used to investigate the structure and evolution of several specific thunderstorm cells and also to examine the life cycle characteristics of 88 intense convective cells during the period from 2000 UTC 20 August to 0400 UTC 21 August 1993. Volume scan data were archived on 8-mm tape at the Radar Data Acquisition site and were analyzed through a variety of means.

The Radar and Algorithm Display Software (RADS; see Eilts et al. 1996) that has been developed at the National Severe Storms Laboratory (NSSL) was used to perform some of the analyses, as were other in-house display programs. The RADS was developed to ingest multiple data streams (e.g., Doppler radar data, radar-based algorithm output, CG lightning flashes, and surface data) and display them simultaneously via graphical products. In-depth analyses were performed by replaying the archive level II data through both the RADS and a Radar Products Generator at the NWS Operational Support Facility (OSF) in Norman, Oklahoma.

Lightning strike information, captured in real-time from the National Lightning Detection Network (see Orville 1994), were used to document CG lightning activity across Arizona on this day. This real-time dataset has been compared to a rigorously quality controlled dataset provided to us by Global Atmospherics Inc. (GAI; K. Cummins 1995, personal communication), and no significant differences were noted. The real-time data were used to create reflectivity and lightning overlays and to calculate trends in time within RADS, allowing a detailed study of the lightning strike characteristics of each intense convective storm cell occurring within 200 km of the radar.

An upper-air sounding [a special sounding using an NSSL Cross-chain Loran Atmospheric Sounding System (CLASS); see Rust et al. 1990] taken at 0000 UTC (1700 LST) 21 August (20 August) 1993 at Luke Air Force Base is shown in Fig. 3. This sounding has moderate instability (e.g., lifted index of −3, totals index of 51, and K index of 43) if lifting occurs. Apparently, mesoscale or small-scale lifting was underway in south-central Arizona since convective storms were in progress about 45 km east-southeast of the sounding location. It is possible that instability

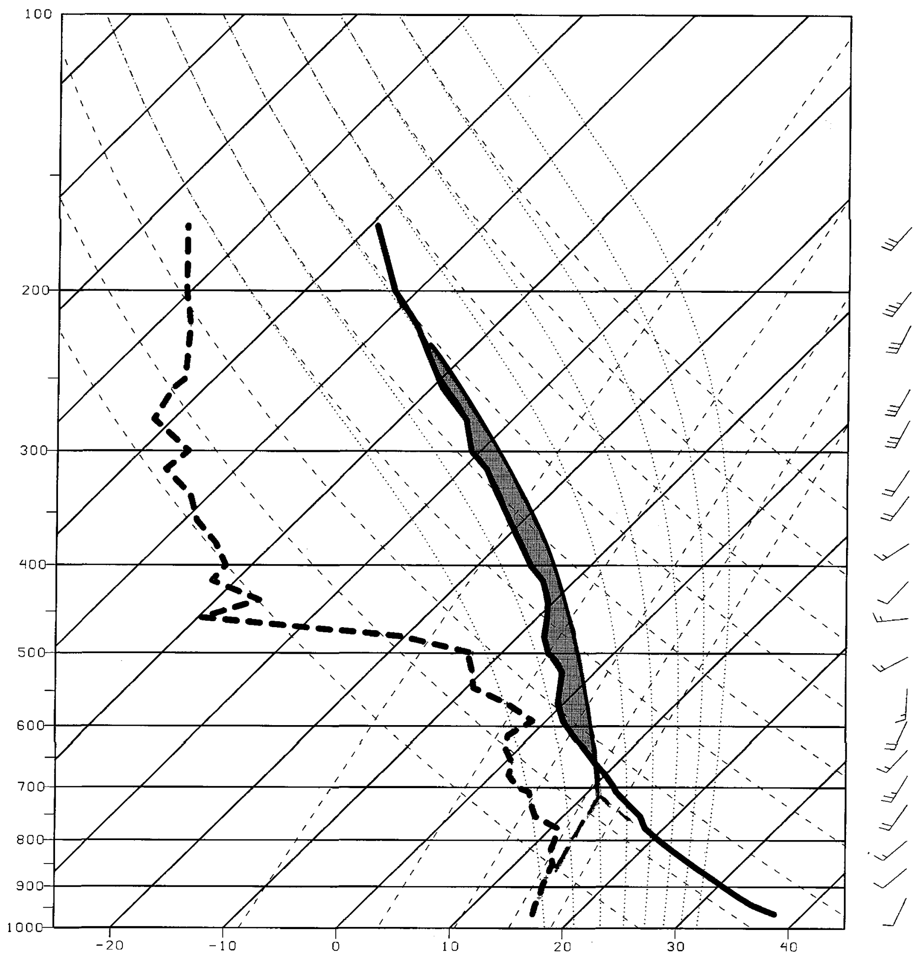


FIG. 3. Upper-air sounding for 0000 UTC taken at Luke Air Force Base (LUF on Fig. 1) on 21 August 1993. Full wind barb equals 5 m s^{-1}.

varied east of the sounding site or at higher elevations; however, this is a difficult issue to address without additional sounding data. The radar analyses, to be discussed later, indicate that the differences in observed CG lightning character were not related to substantial differences in instability.

b. CG lightning character of individual cells

The WSR-88D radar data and the NLDN data have been used to examine the life cycles of six intense convective storms chosen to illustrate the marked differences in CG lightning character that occurred on this day. Figure 4a shows WSR-88D reflectivity data for 0146 UTC, while Fig. 4b is a blowup of the area inside the white square shown on 4a. The Fountain Hills convective cell was located about 28 km from the radar and the Copper Mountain thunderstorm about 82 km from the radar. A cross section of vertical reflectivity structure of the Fountain Hills storm, along P1–P2, is shown in Fig. 4c. (Note that the operational radar scanning strategy did not allow this storm to be fully sampled in the vertical because it was too close to the radar.) The data do indicate that the storm top reached to unknown heights greater than 45 000 ft and that 50-dB*Z* echo reached upward to about 38 000 ft. However, this storm and the Browns Peak cell were intense, convective rainstorms since they produced almost no CG lightning, whereas the Roosevelt Lake and Copper Mountain cells were intense thunderstorms. The Browns Peak and Roosevelt Lake cells were no more than 20 km apart! Terrain elevations beneath the cells (from southwest to northeast) were approximately 2000, 7500, 3000, and 6500 ft above mean sea level. Intense thunderstorms and low-lightning convective storms were occurring over essentially identical terrain elevations.

Radar-observed features of the life cycle of the Fountain Hills and Copper Mountain storm cells are shown in Figs. 5a and 5b during the period between 0115 and 0230 UTC. Note that radar features of the cells are similar—maximum reflectivities are near 65 dB*Z* and reflectivities as high as 55 dB*Z* reached 10 km or higher. All radar indications were that both of these storms were quite intense. The Fountain Hills storm produced extensive wind damage, very heavy rains, and hail up to about half an inch in diameter during the period shown in Figs. 5a and 5b. We have no information available regarding severe weather produced by the Copper Mountain storm since it occurred over very desolate terrain.

The CG lightning activity detected within a 10-km radius of the centroid of these two convective cells is shown in Fig. 5c for each 5-min volume scan period. The difference between the lightning activity associated with the two cells seems remarkable, given that they were less than 90 km apart, had very similar radar reflectivity structures, and were occurring at essentially the same time. The low-lightning character of the Fountain Hills storm was verified by authors KH and CD, who were in Phoenix and able to watch the storm for about 30 min, observing no lightning of any type.

The life cycles of two earlier storms are illustrated in Fig. 6. These two storms, cell numbers 51 and 10, each had maximum reflectivities at 0027 UTC exceeding 60 dB*Z*. Convective storm 51 was severe and produced damaging winds south-southwest of the radar location, whereas storm 10, also very intense, occurred over desolate terrain. The trends in time of several storm attributes are shown (Fig. 6b) from the NSSL RADS analysis package. Although the trends for maximum reflectivity, storm top, and VIL (vertical integrated liquid) are similar, cell 51 produces no detected CG lightning strikes; however, CG strike rates reach as high as 21 per volume scan (i.e., greater than 4 CGs per minute) for cell 10!

c. CG character of all intense cells

The unusually low CG lightning activity associated with several of these intense convective cells was noteworthy because of the extreme severity of the Fountain Hills storm and several others in the Phoenix area (e.g., numerous 1-ft-diameter power poles were destroyed in the immediate vicinity of the radar; winds at Fountain Hills were estimated to exceed 70 kt and widespread damage occurred). The 1ightning strikes associated with a large number of intense, RADS-identified cells in Arizona on this day were examined to provide a better perspective of the CG character of storms on this day. Statistics were compiled for all cells that met the following criteria: (a) occurred within 200 km of the radar, (b) lasted for at least five volume scans (i.e., more than 25 min), (c) maximum reflectivities exceeded 55 dB*Z* for at least one volume scan, and (d)

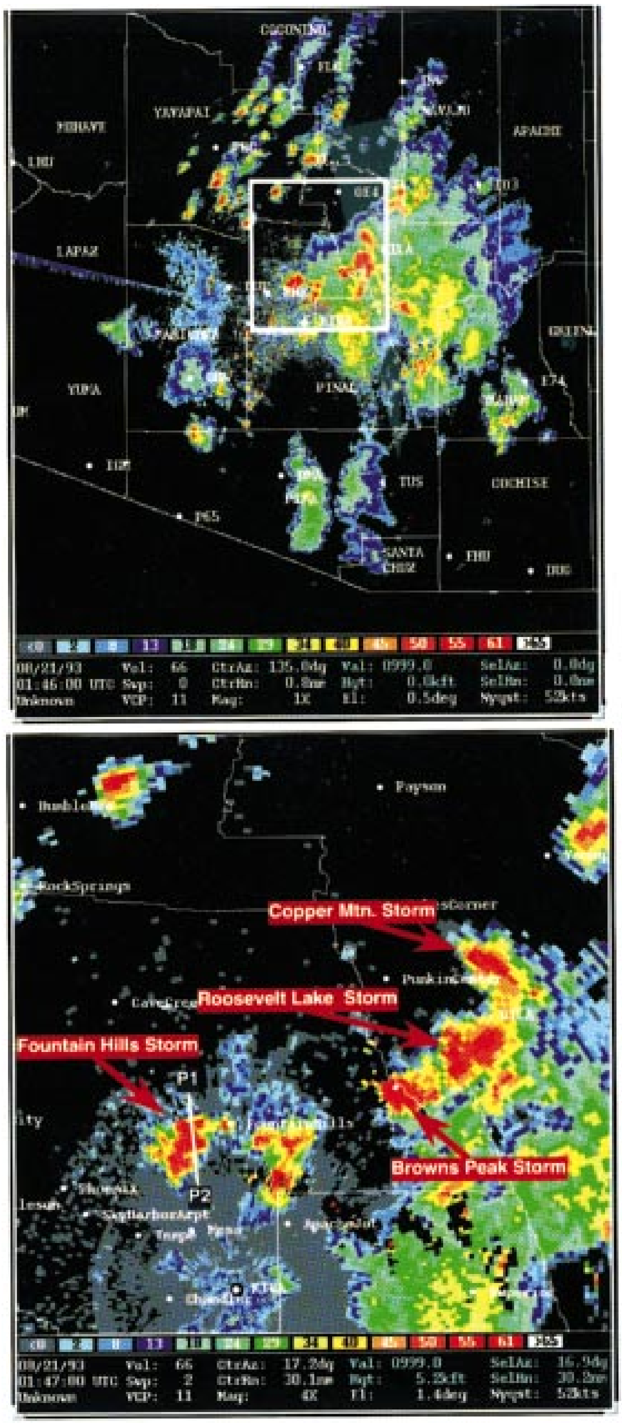


FIG. 4. (a) Radar reflectivities from NWS WSR-88D radar at KIWA for 0146 UTC 21 August 1993. The plot is of ''composite'' reflectivity, the highest reflectivity detected at any elevation angle during the volume scan. (b) Radar reflectivity at an elevation angle of 1.4° enlarged from within the white square shown in panel (a). Four intense convective cells that are referred to in text are indicated. (c) Vertical cross section of reflectivity for the Fountain Hills storm through points P1–P2 [see panel (b)]. Point P1 is to the left and P2 is to the right on this depiction. Note that the radar is also to the right and that the operational sequence of elevation scans does not reach to the top of this storm cell.

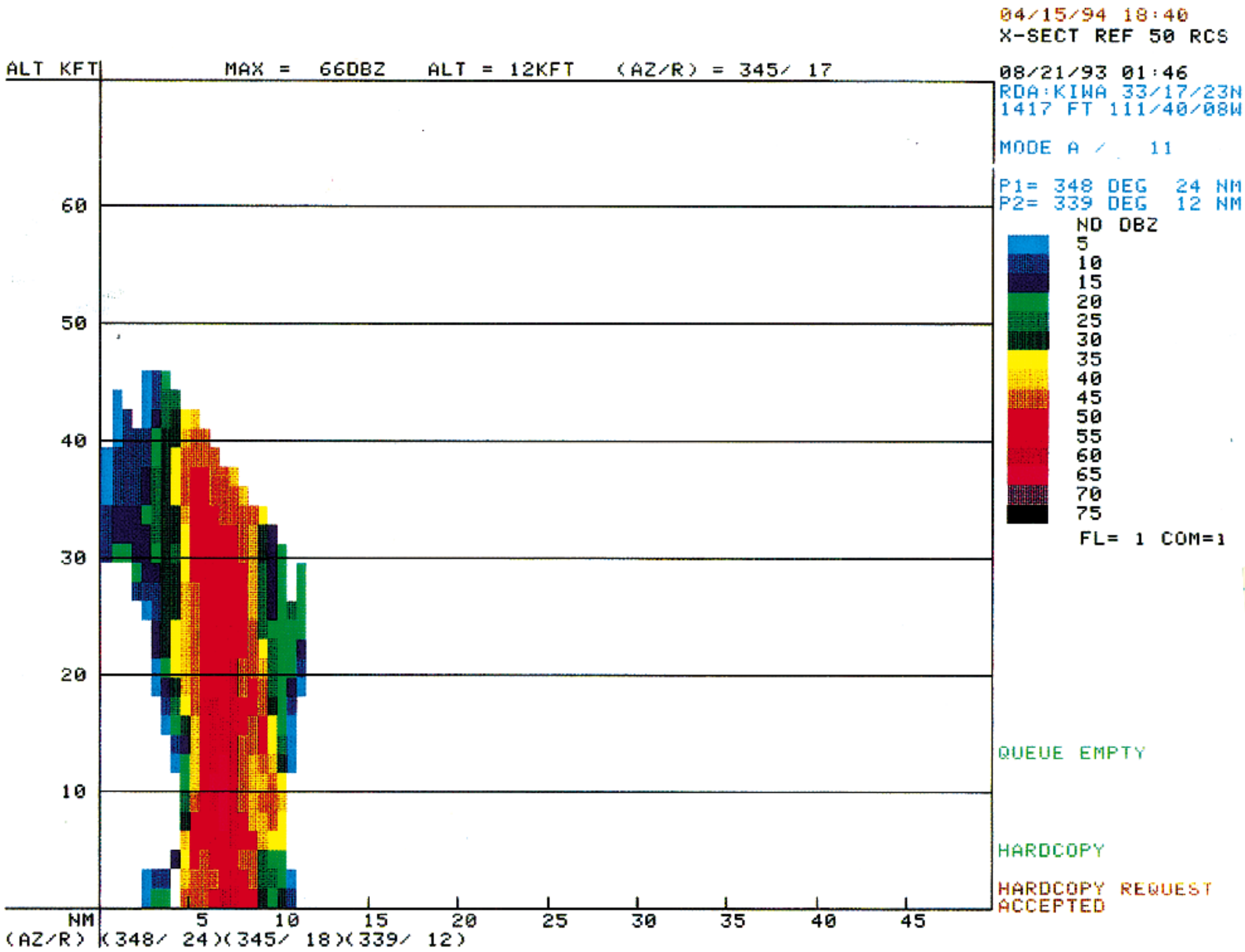
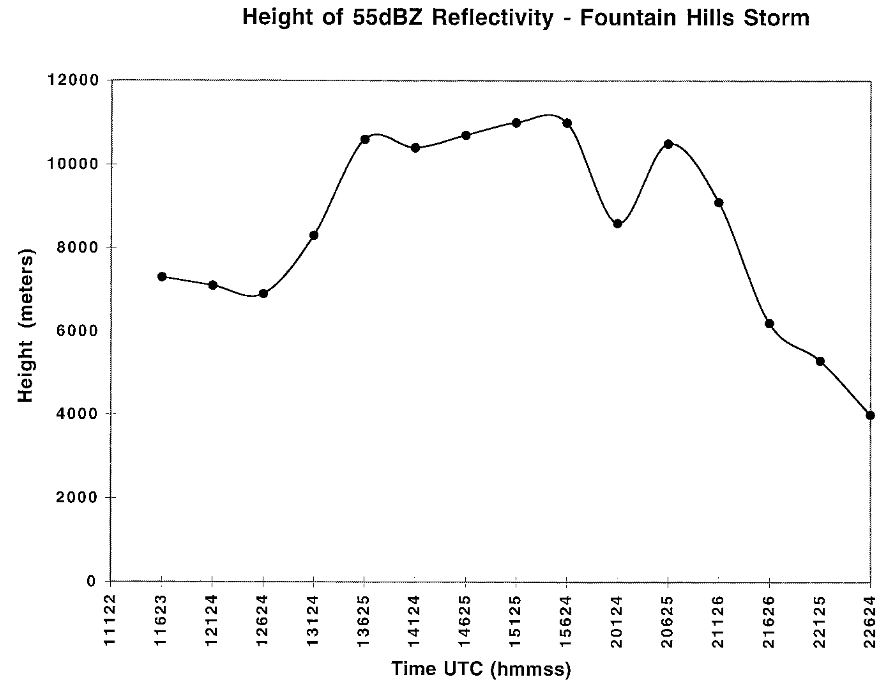


FIG. 4. (*Continued*)

occurred between 2000 UTC 20 August and 0400 UTC 21 August 1993.

The results for the 88 cells that met these criteria are shown in Fig. 7. Averages for the entire life cycle of the storm cells are shown for duration, maximum reflectivity observed during the life of each cell and number of detected CG lightning strikes. The thunderstorms and low-lightning storms are very similar except for the number of detected CGs. Of the 30 low-lightning cells, 10 had no detected CGs strikes during their entire life cycle. One severe convective storm lasted more than 60 min and produced no detected CGs. A number of investigators have shown that the CG lightning strike character (i.e., frequency of CGs and their polarity) of severe thunderstorms often varies dramatically during a storm's life cycle (see MacGorman and Nielsen 1991; Branick and Doswell 1992; Stolzenburg 1994). However, it is apparently very unusual for high top, strong reflectivity severe storms to produce little or no CG lightning during their entire life cycles.

During the 8-h period examined, most storms located anywhere to the west of the radar were low-lightning cells. All storms in eastern Maricopa County were low-lightning cells, even though they were producing hail, high winds, and heavy rains. Storms in western and extreme northern Pinal County were also all low-lightning cells. Storms were of a mixed character over the rest of Pinal County and over the mountains to the east and north of Phoenix. By the end of the 8-h period examined, most of the cells over Gila County were also characterized by low CG production. When the hourly data are examined, it is clear that the zone of low-lightning storm cells progressed east and northeastward from northern Pinal and eastern Maricopa Counties at about 15 kt, moving into western Gila County by the end of the analysis period (which is also the end of significant storm activity for the day).



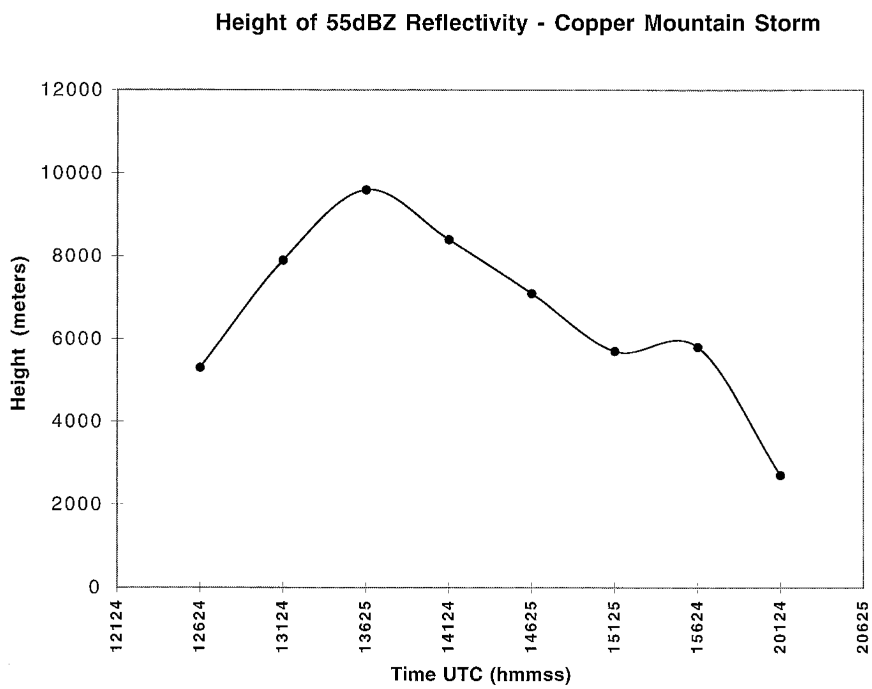
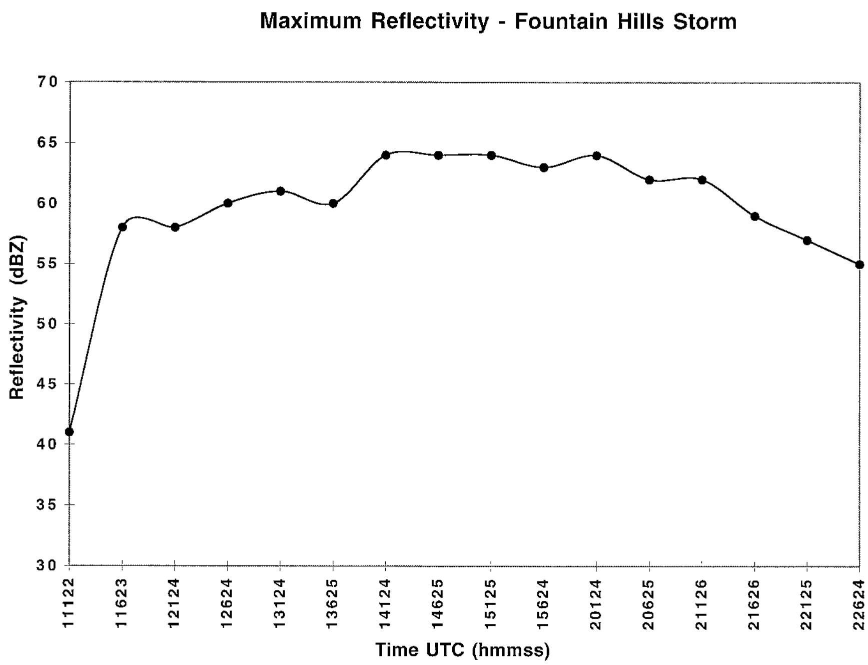


FIG. 5. (a) Time history of the height reached by reflectivities of 55 dB*Z*, (b) height of maximum reflectivity, and (c) CG lightning strike rate for both the Fountain Hills and the Copper Mountain storm cells. Before 0136 UTC the changes in the height reached by reflectivities of 55 dB*Z* and maximum reflectivity are probably not physically real but are artifacts created by the radar scanning strategy (the maximum elevation angle scanned by the WSR-87 is 19.5°) and the closeness of the cell to the radar. After 0136 UTC the "trends" detected by the radar approximate those of the actual storm.



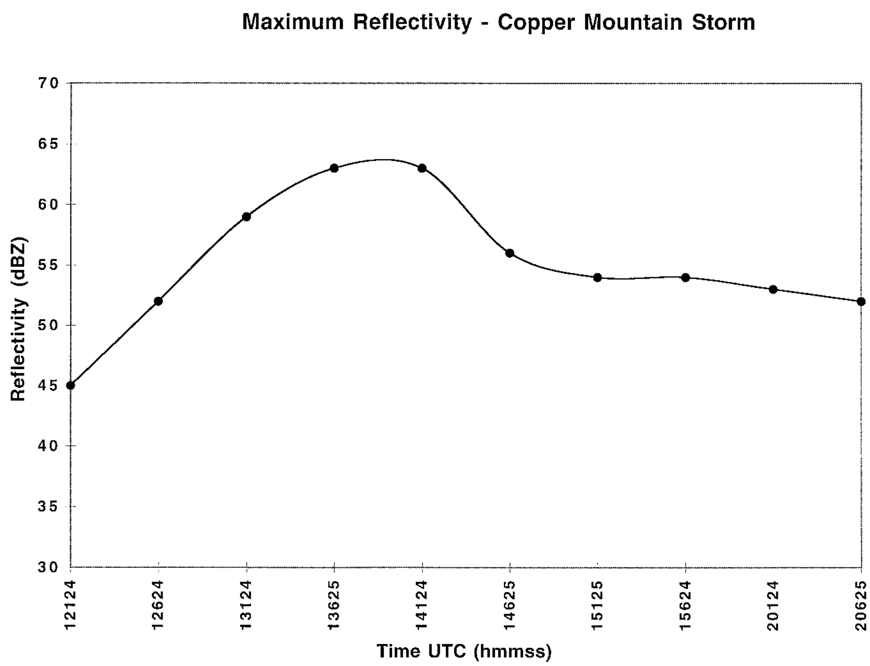


FIG. 5. (*Continued*)

It is perplexing that early storms on the afternoon of 20 August over the mountains both northwest (before the start of the analysis period) and south-southwest of Phoenix were actively producing CGs, whereas intense cells in these same areas had little or no lightning later in the afternoon and evening. It is even more puzzling why the zone of low-lightning storms would shift continuously eastward during the period.

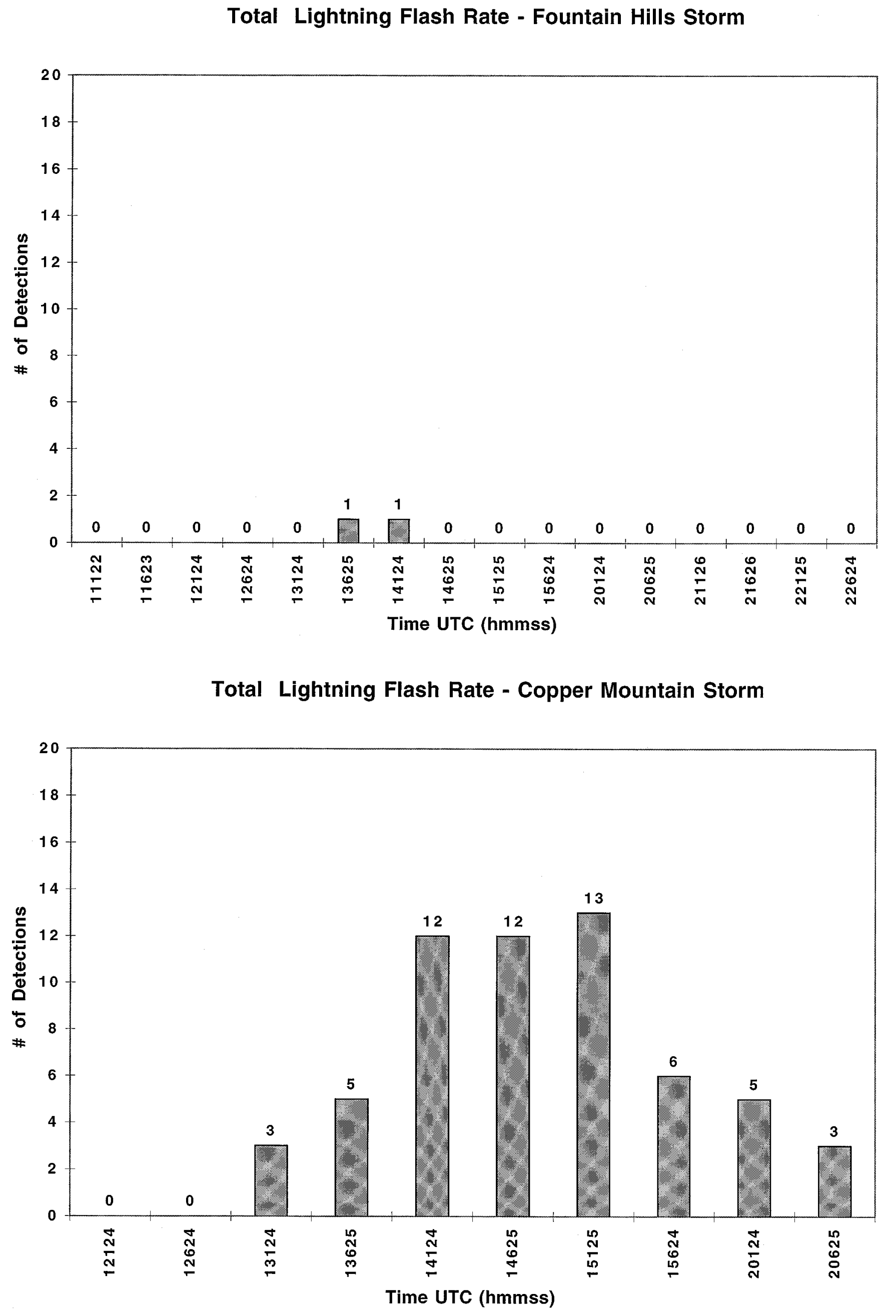


FIG. 5. (*Continued*)

3. Discussion

There are documented physical reasons why different storm cells might produce very different CG lightning activity. The instability of the environment could vary dramatically in space and time, leading to some storms with strong updrafts and others with very weak updrafts. It generally is accepted that strong updrafts, particularly through the region of the convective updraft having temperatures from 0° to −20°C, are needed for storm electrification and lightning (e.g., Workman and Reynolds 1949). Dye et al. (1989) suggested that 40-dBZ reflectivities at the −10°C level were needed for rapid electrification leading to lightning. Zipser and Lutz (1994) have recently presented data showing that oceanic, trop-

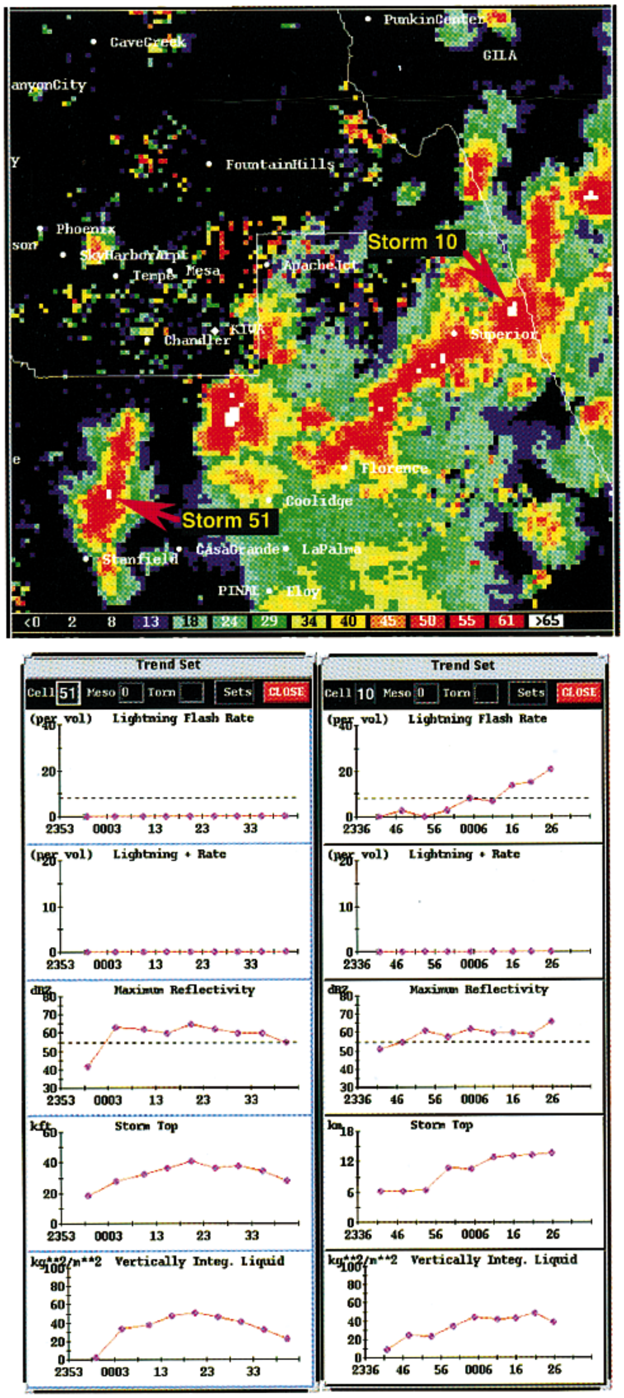


FIG. 6. (a) WSR-88D composite reflectivity display for 0026 UTC 21 August 1993. Storm cells numbers 51 and 10 are identified. (b) Trends of radar-observed cell features for 45-min periods. Note that the starting times are slightly different for the two cells. The ‘‘lightning +’’ window is for positive strikes to ground; neither storm produced any positive strikes.

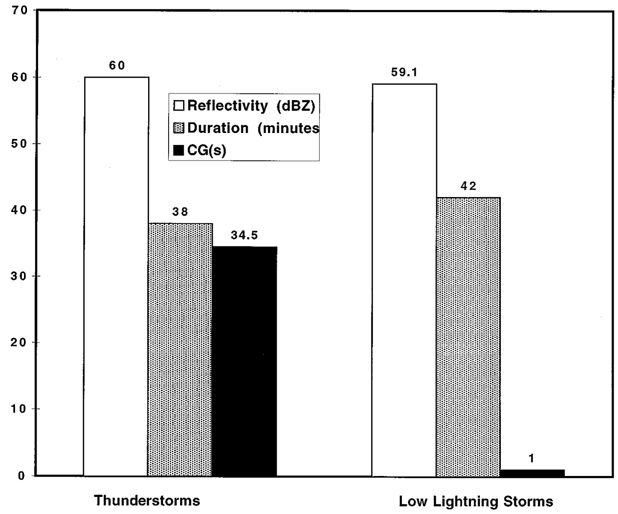


FIG. 7. Mean values of maximum observed reflectivity, duration, and total CG lightning strikes during storm cell life cycles for 58 intense thunderstorms and 30 low-lightning storms observed during period 2000 UTC 20 August–0400 UTC 21 August 1993.

ical convection (which is known to produce relatively little lightning; see Orville and Henderson 1986; Zipser 1994) seldom meets this reflectivity threshold. However, both the CG active and low-lightning cells occurring in Arizona on 20/21 August were continental in character, with very high reflectivities extending upward to levels where temperatures were colder than −40°C. Thus, there is no reason to expect such dramatically different lightning production among cells whose vertical reflectivity structure appeared very similar.

We already have pointed out that some cells were observed in mountainous areas that were active, or inactive, with respect to CGs, depending upon when they occurred. The same was true for low desert areas between Phoenix and Tucson. Thus, the fact that some storm bases were closer than others to the underlying terrain does not seem to be directly related to CG activity on this day.

The strange CG behavior of the storms observed on 20/21 August can not be accounted for with the radar and other meteorological data available. However, when we considered radar data for all of south and west Arizona we noticed that there was considerable chaff being released, apparently during aircraft training missions [we have not been able to verify this because of the classified nature of Department of Defense (DoD) activities], over the military ranges west of Gila Bend. Intense clouds of chaff are easily detected by the WSR-88D; however, as the chaff diffuses it can not be followed by the radar operating in its precipitation scanning mode (i.e., 15 preset elevation angles during a period of approximately 5 min). Figures 8a and 8b show nearly concurrent displays of radar reflectivity and vis-

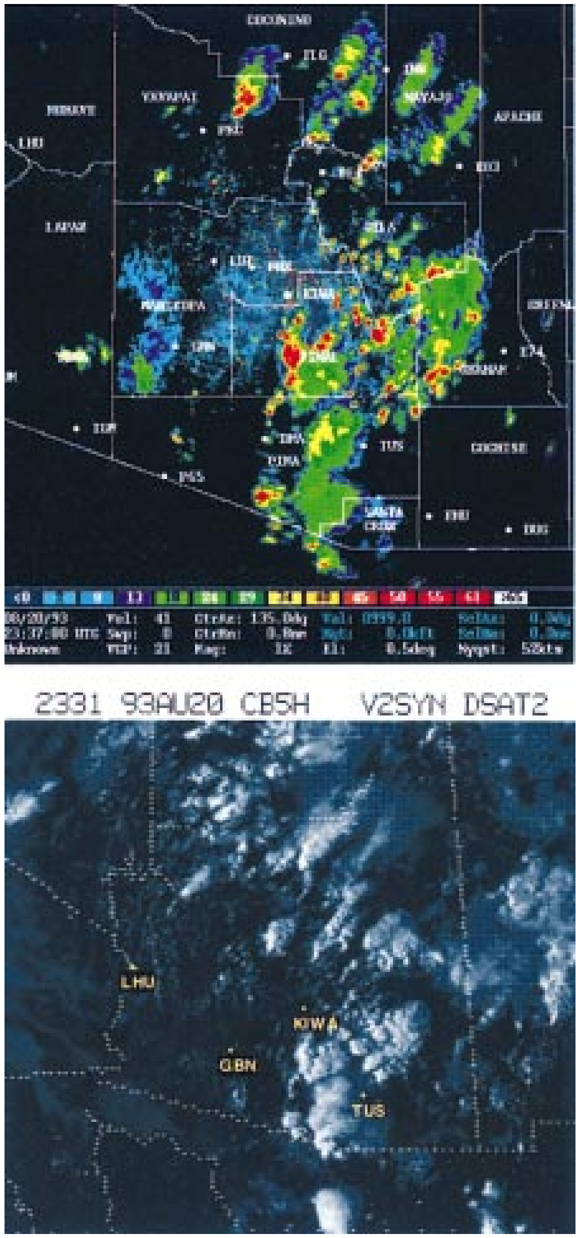


FIG. 8. (a) WSR-88D composite reflectivity display for 2337 UTC and (b) GOES visible image for 2331 UTC, both on 20 August 1993.

ible satellite imagery for Arizona. All of the radar echo in western Maricopa and Lapaz Counties is apparently due to chaff clouds from aircraft releases over the military ranges. There were three distinct ''clouds'' of chaff dense enough to be detected by the WSR-88D during the period of study, and the radar data from the entire day show that the first releases occurred at about 0900 LST.

We hypothesize that an ever-broadening and deepening ''cloud'' of chaff filled the boundary layer on this day over a substantial mesoscale area that extended well beyond the region where the chaff was dense enough to be detected directly by the WSR-88D. This mesoscale ''cloud'' of chaff was being advected to the northeast by the flow below 700 mb, at about 15 kt (see Fig. 3), away from the ranges where aircraft activities and chaff releases were occurring. The storms that developed above this diffuse cloud of ''chaff'' were those that displayed little or no CG lightning activity, whereas storms that formed in essentially the same air mass but outside of the chaff cloud produced frequent lightning strikes to ground.

The approximate delineating line between thunderstorm cells and the low-lightning cells is shown in the analyses presented in Fig. 9. These analyses were developed by plotting the positions and times of observations of all the 88 intense cells examined. Cells to the west of the heavy yellow line were low-lightning cells. The position of the delineator is shown at 2-h intervals, along with radar echoes, in Figs. 9a–c, and the hour by hour subjectively analyzed positions are shown in Fig. 9d. The delineating line moves eastward and northward at approximately the speed of the mean wind below 700 mb (see Fig. 3) it does appear that the demarcation line does move, or deform, up the valleys north, east-southeast, and southeast of Phoenix (refer to the terrain elevations shown on Fig. 1). This could reflect the afternoon valley–mountain circulations that routinely occur in these areas.

Field studies in the past have shown that chaff seeding results in the production of corona discharge that causes a discharging current to flow within a developing or active thunderstorm (Rust and Krehbiel 1977). The effects of chaff seeding on thunderstorms was explored during two small field campaigns in Colorado during 1972 and 1973. These programs were described by Holitza and Kasemir (1974) and Kasemir et al. (1976). The results of these projects indicated that the electric fields below thunderstorms seeded with chaff decay from 5 to 10 times faster than the fields below nonseeded thunderstorms. The field data also indicated that seeding ongoing thunderstorms with chaff reduced the number of CGs observed to a third or less of that of a control group of nonseeded thunderstorms.

Considering these previous findings on thunderstorms and chaff, we feel that the chaff releases that occur routinely over the DoD ranges of south-central and southwest Arizona likely are modifying the electrical character of deep convective storms that ingest diffuse, but widespread, chaff clouds drifting away from the ranges, into their updrafts. At NSSL we have compiled a substantial database of radar, satellite, and sounding data that will allow us to investigate this likelihood more thoroughly and rigorously.

Acknowledgments. The authors thank the staff of the

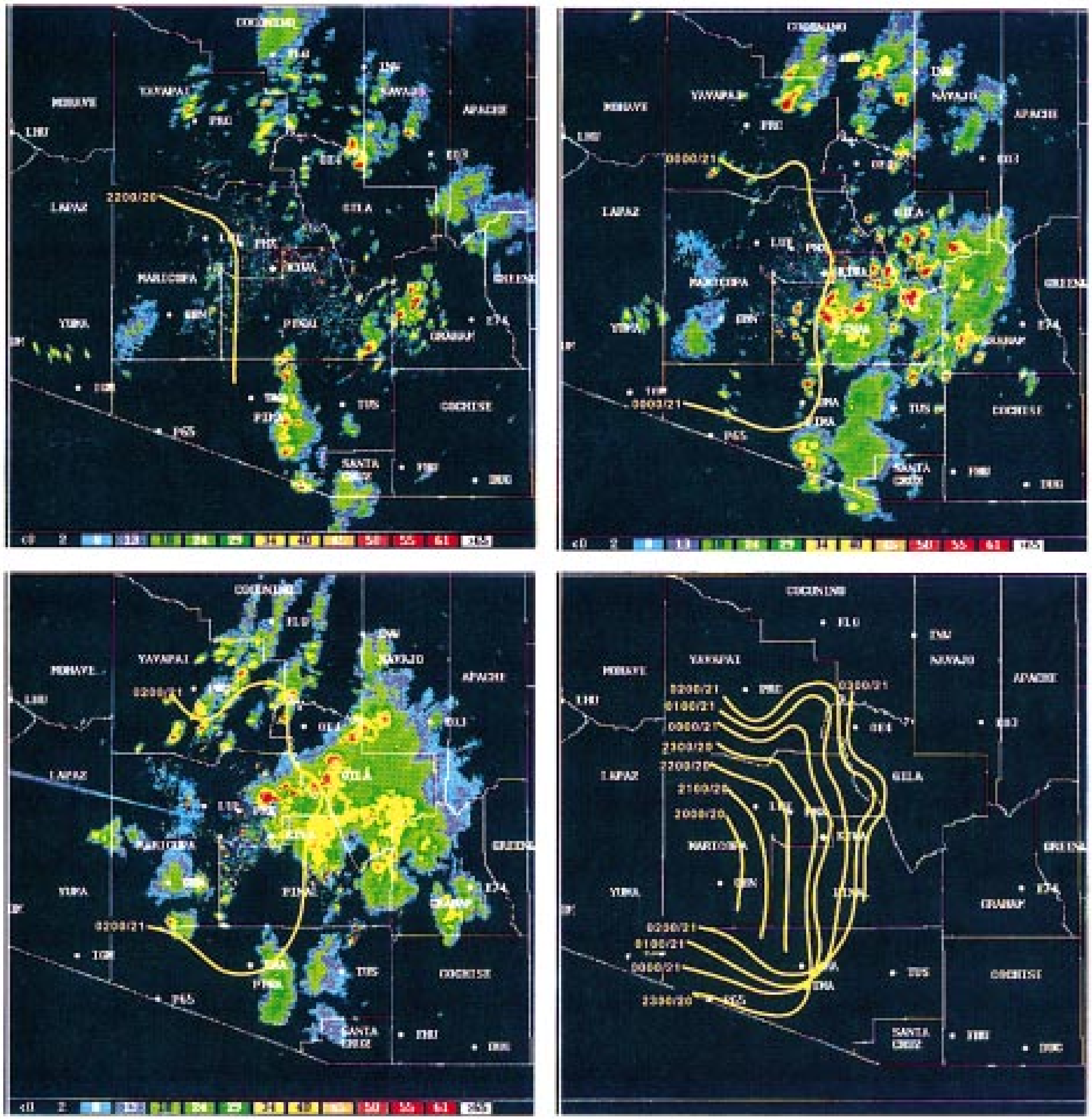


FIG. 9. (a)–(c) Composite reflectivity charts showing location of thunderstorms and low-lightning storms for 2200, 0000, and 0200 UTC 20/21 August 1993. The storms east, north, and south of the yellow line are thunderstorms with CG lightning strikes, while the cells west of the yellow line are low-lightning storms. (d) Hourly positions of the line separating intense thunderstorms from low-lightning storms for the analysis period.

Weather Detachment at Luke Air Force Base for taking the upper-air soundings during the summer of 1993. Dr. David Rust discussed the results of the Colorado lightning modification field experiments with author RM and provided reprints of relevant papers. Mr. Ken Cummins of GAI provided copies of their high-quality lightning strike database for us to use. The comments and suggestions of three anonymous reviewers helped us to make substantial improvements in the presentation of this work.

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