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TOTAL LIGHTNING, RADAR AND SATELLITE OBSERVATIONS OF TWO MONSOON THUNDERSTORM EVENTS IN THE TUCSON AREA IN SUMMER 2007

Erik Pytlak
NOAA/National Weather Service, Tucson, AZ

Martin Murphy, Nicholas Demetriades, and Ronald Holle
Vaisala Inc., Tucson, AZ

1. INTRODUCTION

Southeast Arizona lies on the northern edge of the North American Monsoon System (Carleton 1985; Douglas et al. 1993). Between late June and late September, most of southeast Arizona, including the Tucson Metropolitan area, receives about half of its normal annual precipitation (Higgins et al. 1997), with most of the rain falling in association with thunderstorms. Lightning activity is prolific during this time of year. Portions of the Sierra Madres about 500km south-southeast of Tucson appear to have the greatest annual cloud-to-ground (CG) flash densities of any location in North America (Murphy and Holle 2005).

The large scale North American Monsoon flow regime develops as the continental subtropical high forms over Mexico in June (Figure 1), and strengthens as it shifts into the southern Rockies in July (Figure 2). Northwest Mexico and much of Arizona fall under the influence of the tropical easterlies which transport considerable mid- and upper-level moisture into the region. At lower levels, differential heating between the land and adjacent warm water bodies causes flow reversals (Tang and Reiter, 1984), which import considerable moisture into the monsoon region. Evapotranspiration, particularly from the subtropical rain forests of the Sierra Madre Occidental (Watts et al. 2007) can also contribute to moisture availability for thunderstorm initiation and development.

The exact location of the subtropical high on any given day governs not only the possibility of organized thunderstorms (Douglas 1992; Watson et al. 1994), but also their potential severity (McCollum 1993; Maddox et al. 1995). Either because of the alignment of the subtropical high itself (Vasquez 1993; Blanchard et al. 1998), or because of the passage of transient upper level disturbances (Pytlak et al. 2005; Douglas and Englehart 2007), large Mesoscale Convective Systems (MCSs), with cloud top temperatures occasionally colder than -70°C, periodically organize over Arizona. Individual thunderstorms within these MCSs can produce damaging winds, torrential rains, and prolific lightning.

During the monsoon, thunderstorms develop on a regular basis over the high terrain and frequently move off into the lower deserts. Thus, lightning activity generally tends to be greatest where the terrain is higher. For this reason, southern Arizona lies in a gradient of annual CG lightning flash density, with less than 0.5 flashes/km^2/year in low desert areas from the Phoenix metropolitan area westward to the Colorado River (Orville and Huffines, 2001), and values of around 8 flashes/km^2/year in higher terrain just south of the Mexican border near Douglas and Bisbee, Arizona (Murphy and Holle, 2005). Typically, 95-99% of CG flashes in southern Arizona lower negative charge-to-ground (Orville et al., 2002). The primary sources of positive CG flashes in southern Arizona are the stratiform regions of small MCSs that propagate westward into the lower deserts. However, flash densities in MCS stratiform regions are typically much smaller than in the leading convective lines or clusters (e.g. Rutledge and MacGorman 1998; Holle, et al. 1994), so that negative CG flashes still dominate heavily even in MCSs. Finally, Boccippio, et al. (2001) showed, using a combination of satellite optical and U.S. National Lightning Detection Network (NLDN) observations, that the ratio of cloud lightning flashes to CG flashes in higher-terrain areas of the interior western U.S., including southern Arizona, is only slightly higher than 1. That is to say that CG flashes typically account for one third to nearly one half of the lightning activity in this region, according to their analysis. Even considering potential uncertainties in the combined satellite-ground analyses, CG flashes probably account for one quarter to one third of the lightning activity in southern Arizona on a climatological basis.

In this paper, we analyze two very different thunderstorm situations that occurred during the 2007 monsoon. These storms were observed by a new total (cloud plus CG) lightning mapping system installed in the Tucson region just prior to the 2007 monsoon onset. The first case was a large MCS on 24 July that produced severe weather and exhibited very unusual lightning characteristics for southern Arizona. The second was a smaller MCS on 10 August that also produced severe weather in its earlier stages despite somewhat less favorable conditions for severe weather. We first discuss the observations used in the analysis of these two storms, and then we present the detailed meteorological analysis of the storms.

2. INSTRUMENTATION, OBSERVATIONS AND METHODS

2.1 LS8000 Total Lightning Mapping Network

The major new contribution to the understanding of the lightning activity in the 24 July and 10 August storms comes from the mapping of total lightning activity over the Tucson region. In early summer of 2007, Vaisala installed a new network of LS8000 total lightning mapping sensors around the region. Figure 3 shows the layout of the four sensors in this network. Each of these sensors consists of a VHF interferometer that measures the angle of incidence of VHF emissions from lightning discharges. The sensors also contain a second antenna system that measures the angle of incidence and time-of-arrival of LF/VLF signals in the same way as the NLDN. VHF emissions are produced in abundance by cloud lightning flashes (e.g. Shao and Krehbiel 1996) and the in-cloud components of CG flashes (e.g. Mazur, et al. 1995), and therefore, ground-based sensing systems such as the LS8000 are capable of mapping out the spatial extent of each lightning flash.

The expected performance of the Tucson LS8000 network is shown in Figures 4 and 5, which present model estimates of the flash detection efficiency and the location accuracy of individual VHF emissions, respectively. The principal limiting factor for detection efficiency in any VHF system is blockage of the signals by terrain or buildings, given that the signals propagate along a line of sight between the source and each sensor. The four sites of the Tucson system have been chosen for their excellent visibility over the Tucson metropolitan area and to the northwest of Tucson where terrain altitude is considerably lower (Figure 4). The system also has good visibility over much of the area to the southeast of Tucson in the higher terrain. Figure 5 shows that the expected location accuracy for individual VHF emissions is at or below 1 km over most of the area where detection efficiency is high. Location accuracy is limited primarily by noise and by the fact that the emission sources are not stationary during the interval of observation. Both of these effects artificially inflate the effective random angle error. However, the true location accuracy, taking these effects into account, is expected to be within a factor of 2 of what is shown in Figure 5, and this is more than sufficient for the work presented in this paper.

Detection efficiency has been verified by comparing clusters of VHF emissions to CG flashes detected by the NLDN (Lojou, this conference), and it has been found to be at or near 100% over the entire Tucson metro area. Location accuracy is less readily quantified, but residual random angle errors have been observed for VHF emissions detected by at least 3 of the sensors, which provide redundant information for the determination of the emission source positions. For a large number of such events in the summer of 2007, the random angle errors were between 1.0 and 1.5 degrees. This is consistent with a median location error of approximately 1 km in the interior of the network, which is approximately what the model shows in Figure 5.

Typically, a number of VHF emissions are detected in each lightning flash. To obtain flash-level information, we group the individual emission source locations (hereafter "sources") into flashes using an algorithm described by Lojou and Cummins (2005). This algorithm uses maximum distance and time separation windows to find the most physically reasonable connection between VHF sources within each flash. An example of how the algorithm connects the sources in a single flash together is shown in Figure 6.

2.2 National Lightning Detection Network (NLDN)

Although the LS8000 sensors have LF/VLF antenna elements capable of sensing CG lightning, this portion of the LS8000 system was not used in this study. Rather, CG lightning information was taken from the NLDN. Following an upgrade of the system in 2003, Biagi et al. (2007) measured the flash detection efficiency and location accuracy of the NLDN in southern Arizona. The DE for CG flashes is over 90%, and the median location accuracy is just over 400 meters. These observed values are slightly better than earlier model-based estimates for the region.

2.3 NWS radar, satellite and surface storm reports

The National Weather Service Forecast Office in Tucson, Arizona, maintains a daily archive of radar, satellite, numerical weather prediction (NWP) model, upper air, and surface observation data during the monsoon season. This data, which is collected by the NWS Advanced Weather Information and Processing System (AWIPS) is stored off-system using the NWS Warning and Decision Training Branch Warning Event Simulator (WES) archive. Both systems enable forecasters to view radar data in both plan and cross section views.

3. METEOROLOGICAL SITUATION AND TOTAL LIGHTNING DEPICTIONS

3.1 24-25 July 2007

The atmosphere was primed across southeast Arizona to support widespread thunderstorms, some severe. A large upper tropospheric low was moving west from Texas, with another upper low moving north into southern California (Figure 7). In between, an area of strong upper level stretching deformation and divergence was noted from Sonora, Mexico, all the way into the northern Rockies. The location and movement of the Texas upper low fit the conceptual model of Pytlak et al. (2005) for inverted troughs and their likelihood to enhance MCS development. The 500mb subtropical high was located along the Utah-Colorado border, which is typical of a Type I Arizona severe thunderstorm pattern (Maddox et al. 1995). By late in the afternoon on the 24^{th}, the NWS Tucson upper air sounding indicated deep and significant instability with a Mean-Layer Convective Available Potential Energy (MLCAPE) near 2000 J/kg (Figure 8). Near-surface, upvalley, northwest winds around 7 m/s were noted, with winds at 4-5 km MSL out of the southeast approaching 10 m/s. With much of the wind above the level of free convection out of the southeast with only a modest increase with height, strong cold pools would tend to limit the longevity of individual thunderstorms. However there was enough wind shear present for storms to cluster, merge, and become intermittently severe. Anvil level winds were generally out of the northeast at 3-7 m/s.

This is exactly how the Mesoscale Convective System initially took shape. At 22:00 UTC 24 July, severe thunderstorms had already erupted over the higher terrain southwest, south, and southeast of Tucson (Figure 9). By 00:15 UTC, the thunderstorms southwest of Tucson weakened, while the thunderstorms southeast and east of Tucson had merged over Central Tucson and had become quite severe (Figure 10). Multiple wind damage reports were received between 00:15 and 00:30 UTC as this cluster propagated discontinuously upshear toward the northwest.

It is at this point when interesting developments began in the anvil region of the MCS. By 01:00 UTC, the strongest surface-based thunderstorms were on the north and east flanks of the MCS anvil (Figure 11). However, the storm north of the MCS anvil produced only a few positive cloud-to-ground (CG) lightning strikes, while the storms to the east produced numerous negative CG strikes. Meanwhile, cloud top temperatures over 30 km away from the nearest 40+ dbZ core cooled dramatically to less than -80°C (Figure 12). Under this anvil, no CG strikes were detected by the NLDN, yet almost continuous intracloud lighting and rumbling thunder was observed throughout Tucson. By 02:00 UTC, with the strongest cells almost 70 km away from central Tucson, minimum cloud top temperatures were -84°C. Meanwhile a second cold cloud top was observed east of Tucson about 50 km away from the nearest weakening storm. Even after 03:00 UTC when most of the strong thunderstorms had dissipated or had moved northwest toward Phoenix, Arizona, cloud top temperatures between -60°C and -83°C remained over Tucson and eastern portions of the metro area where light rain continued at the surface.

Figure 13 presents a time series of the lightning activity in the storms that passed over the Tucson metro area from south to north, including activity in the cold cloud shield ("anvil" portion). This captures the cells that produced small amounts of positive CG flashes and deliberately omits cells farther east that produced larger amounts of negative CG lightning. In Figure 13, cloud flash ("IC") rates are shown on the left-hand axis, and CG flash rates on the right, and the vertical scale on the left-hand side is 25 times that on the right. The lightning activity was separated into the leading convective portion of the storm and activity that occurred underneath the anvil. We first note that CG flashes were extremely rare in both the convective and anvil portions of this storm. In the convective portion, the CG flash rate rarely exceeded 2 per 5 minutes and never exceeded 5 per 5 min. Only 3 CG flashes were produced by the anvil portion during the entire storm. The time series also showed a sharp increase in cloud flash rate in the anvil portion at 01:20 UTC. From a detailed analysis of lightning during short periods of time, we know that one of the main convective cells appeared to become stationary and embedded within the cold cloud shield somewhere between 01:15 and 01:30. The exact time of the transition is uncertain, but after the transition, there was a clear physical separation between the activity in the anvil and the activity in the main convective cells, and the lightning rate under the anvil was comparable to that in the convective portion for some time. Finally, although not shown in the figure, most of the CG flashes were of positive polarity.

Radar cross sections through the Tucson metro area revealed that convective towers were present well behind the surface-based thunderstorms. At 01:15 UTC, 30-45 dbZ elevated echo cores were noted near the freezing level, with multiple towers (reflectivities >20 dbZ) extending all the way up to the -40°C layer (Figure 14). These towers, while clearly convective in nature given their cellular structure and depth, were squarely within what would normally be the “stratiform” anvil region.

3.2 10-11 August 2007

Although not nearly as impressive as 24-25 July 2007, the synoptic and thermodynamic situation on 10-11 August 2007 was again favorable for strong thunderstorms to loosely organize into a small, albeit relatively warm-topped, MCS. A weak upper level tropospheric low was situated over the central Gulf of California and was beginning to elongate as a much stronger and larger upper low moved west from the western Gulf of Mexico. Once again, southeast Arizona was in an upper level stretching deformation area on the fringes of the Gulf of California system (Figure 15). The 00:00 UTC WFO Tucson sounding also was less unstable than the July 24-25 case, but did indicate at least some instability with a modified MLCAPE approaching 1000 J/kg, and low level bulk shear around 10 m/s (Figure 16). The main threat in this case would usually be from wet or hybrid microbursts due to an unusually high precipitable water of over 39 mm.

Isolated thunderstorms developed rather late in the afternoon near the mountains north and east of Tucson (Figure 17). By 00:30 UTC on 11 August, the isolated storms had collided over the north side of Tucson, and by 01:15 UTC, had become severe with hail diameters approaching 2.5 cm and at least two reports of wind damage on the northwest side of Tucson (Figure 18). By 02:00 UTC the cluster had moved northwest toward Phoenix, while a small but cold MCS anvil spread back over the Tucson Metro area (Figure 19). The storm cluster weakened by 03:00 UTC, yet the MCS anvil remained quite cold (Figure 20) north of the Tucson metro area with little rain falling underneath.

A reflectivity cross section from this event showed a more typical and much more benign stratiform precipitation region (Figure 21). The precipitation shield was more stratiform in appearance, with no tower development noted near the freezing level.

Figure 22 shows the time series of lightning activity in the 10-11 August case. The format is somewhat different from Figure 13, in that here, we show both cloud ("IC") and CG flash rates on the same vertical scale, and the scale is logarithmic in order to capture both low- and high-rate phases of the storm well. Prior to 00:30 UTC when the cell collision occurred, total flash rates were low, and CG flash rates were comparable to cloud flash rates. This is typical of the lightning activity in typical severe thunderstorms in southern Arizona. Even after the cell collision, CG flash rates and cloud flash rates were in phase with each other until nearly 01:00 and again after 01:30. CG flash rates were also much higher than in the 24 July case, peaking near 20 flashes per 5 min. Between 01:00 and 01:30, there was a significant increase in cloud flash rate, to nearly 200 per 5 min, with a simultaneous decrease in CG flash rate. The peak cloud flash rate and minimum in CG rate were simultaneous with the large hail and severe wind reports.

4. DISCUSSION AND CONCLUSIONS

While the predominant anvil lightning event on 24 July 2007 has not been quantitatively observed in southeast Arizona until now, cases in which secondary lightning development occurred within MCS anvils have been documented. Many of these cases involved trailing squall line anvils (e.g. Schuur, et al. 1991), including one such event observed by a total lightning mapping network (Steiger, et al. 2007). Rutledge and Petersen (1994) proposed that in-situ charging can take place within the stratiform anvil region of both mid latitude and tropical MCSs, and at least somewhat independently of the deep convection that initiated anvil development. They suggest that enough supercooled water is sometimes present to permit non-inductive charge separation, most likely when radar reflectivities within the mixed phase region exceed 15 dBZ. They also suggest that this in situ charging can be associated with embedded convection within the stratiform region. Dye and Willett (2007) examined a case in which long lived anvils also underwent secondary convective redevelopment, which was accompanied by dramatic increases in intracloud lightning. In their case, radar imagery suggested that updrafts redeveloped within the anvil itself, enough to support convective towers within the “stratiform” anvil.

In the 24 July 2007 case, both radar cross sections and lightning initiation locations imply that there were separate convective towers developing within the larger anvil portion of the storm. Radar reflectivities near the bases of the secondary anvil towers reached 40 dBZ coincident with the estimated freezing level. That strongly suggests that significant liquid precipitation, water-covered ice particles, and/or rime ice was present. In less reflective parts of the anvil where significant intracloud lightning was also present, bases near the -4°C isotherm still exhibited radar reflectivites as high as 30 dBZ with 20 dbZ towers extending as high as -40°C, consistent with the embedded convection explicitly noted by Dye and Willett (2007). Regardless of charging mechanism, it is very likely that the 24 July event was a case of in-situ charge separation in embedded anvil convection.

What is most interesting about the 24 July case is the almost total lack of CG lightning, as well as the fact that most of the few CG flashes were of positive polarity. This is very reminiscent of lightning activity that has been observed in severe thunderstorms in the western Great Plains (e.g. Wiens, et al. 2005; Tessendorf, et al. 2007a and b). In the Great Plains, a growing body of evidence suggests that positive CG flashes dominate when the cloud electrical structure is inverted from the normal polarity (MacGorman, et al. 2005). Cloud flashes apparently dominate when the storm charge is raised to high altitude by a very strong updraft or when the lowest-altitude charge region is deep and creates a strong potential well that prohibits discharges from propagating to ground. In the Great Plains, it appears that both of these lightning characteristics (high cloud lightning rate and the dominance of positive CGs among the relatively few CG flashes that are produced) are frequently associated with storms having a strong updraft and severe weather. It has been suggested that relatively high cloud bases are correlated with broad, strong updrafts that suffer relatively little entrainment (Williams, et al. 2005) and that this also coincides with a shallow warm cloud layer, which leads to greater liquid water content in the mixed-phase region of the cloud and tends to favor the inverted charge structure (Carey, et al. 2003). However, it is not at all clear how much of this applies to southern Arizona thunderstorms, where cloud bases are quite high on a daily basis, yet most storms are of the air-mass variety, produce a relatively large amount of CG lightning, and produce predominantly negative CG flashes. Furthermore, in the specific case of 24 July, both convective and embedded anvil-region cells had lightning characteristics similar to Great Plains severe storms, yet the vertical reflectivity profiles suggest that the updrafts in the embedded anvil cells would have been weak to moderate in strength.

The ability of an NWS office to forecast which MCSs will undergo significant anvil redevelopment may not seem important initially. Both the 24 July and 10 August cases produced severe weather.

However the secondary, intra-anvil development in 24 July case posed a potential threat to not only public safety, but also aviation. The strongest thunderstorms had moved well away from the Tucson metro area, with a light, gentle rain keeping temperatures pleasantly cool on what would normally be a hot, humid summer evening in Tucson. Such welcome evenings tend to draw residents outdoors for activities. However with a highly electrified anvil over the metro area for several hours, positive cloud-to-ground lightning strikes were a constant threat. Perhaps more seriously, this was a potentially serious threat to high altitude aviation (i.e. commercial aircraft) crossing southern Arizona. In this case the normally benign anvil region was actually quite convective with updrafts strong enough to induce charge separation. Aircraft flying through such an environment would not only have encountered significant turbulence, but also significant and unexpected icing since instead of flying through mainly non-adhering ice crystals, a hapless aircraft would be flying through a large area of mixed phase ice which would easily adhere to an airframe. Descending to lower atmospheric levels would make such an already impacted aircraft vulnerable to virga or light rain downdrafts.

Environmentally, the difference between the 24 July and 10 August cases was that both CAPE and low level shear were stronger in the 24 July case. In addition, anvil level winds were somewhat stronger and more coherently out of the northeast during the 24 July event, while in the 10 August case, anvil level winds were nearly calm. In both cases, classic severe weather did occur. However in the 24 July case, environmental conditions would have normally supported more widespread surface-based thunderstorms than actually occurred. One can speculate on why more numerous, strong thunderstorms did not develop. Given the presence of moderate low-level shear, enough CAPE remained in the environment to support secondary development above the surface cold pools generated by the initial convection. The authors have no way to know how unstable the atmosphere remained aloft over the Tucson metro area on these days. Further study on similar events would obviously need to confirm that higher CAPE, moderate shear, lingering CAPE above surface cold pools, and at least some coherent anvil-level flow are all needed to support intense secondary convection within the normally stratiform anvil region of an MCS.

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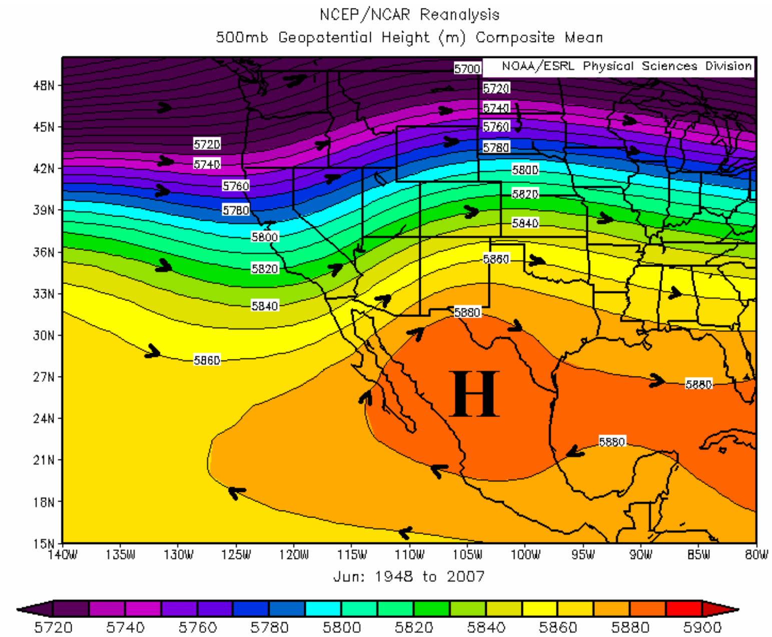
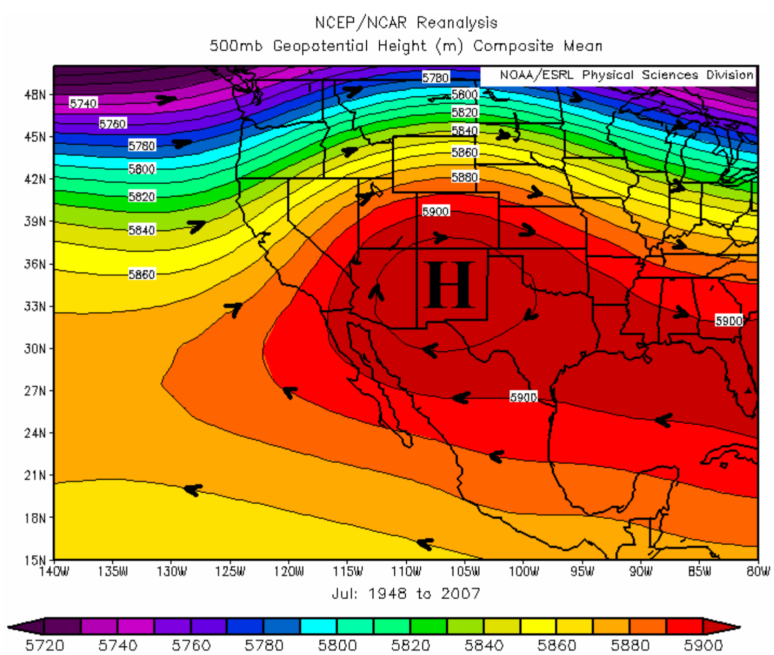


Figure 1: NCEP/NCAR reanalysis, mean 500mb heights and flow, June. Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov.



i**Figure 2:** Same as Figure 1, except for July.

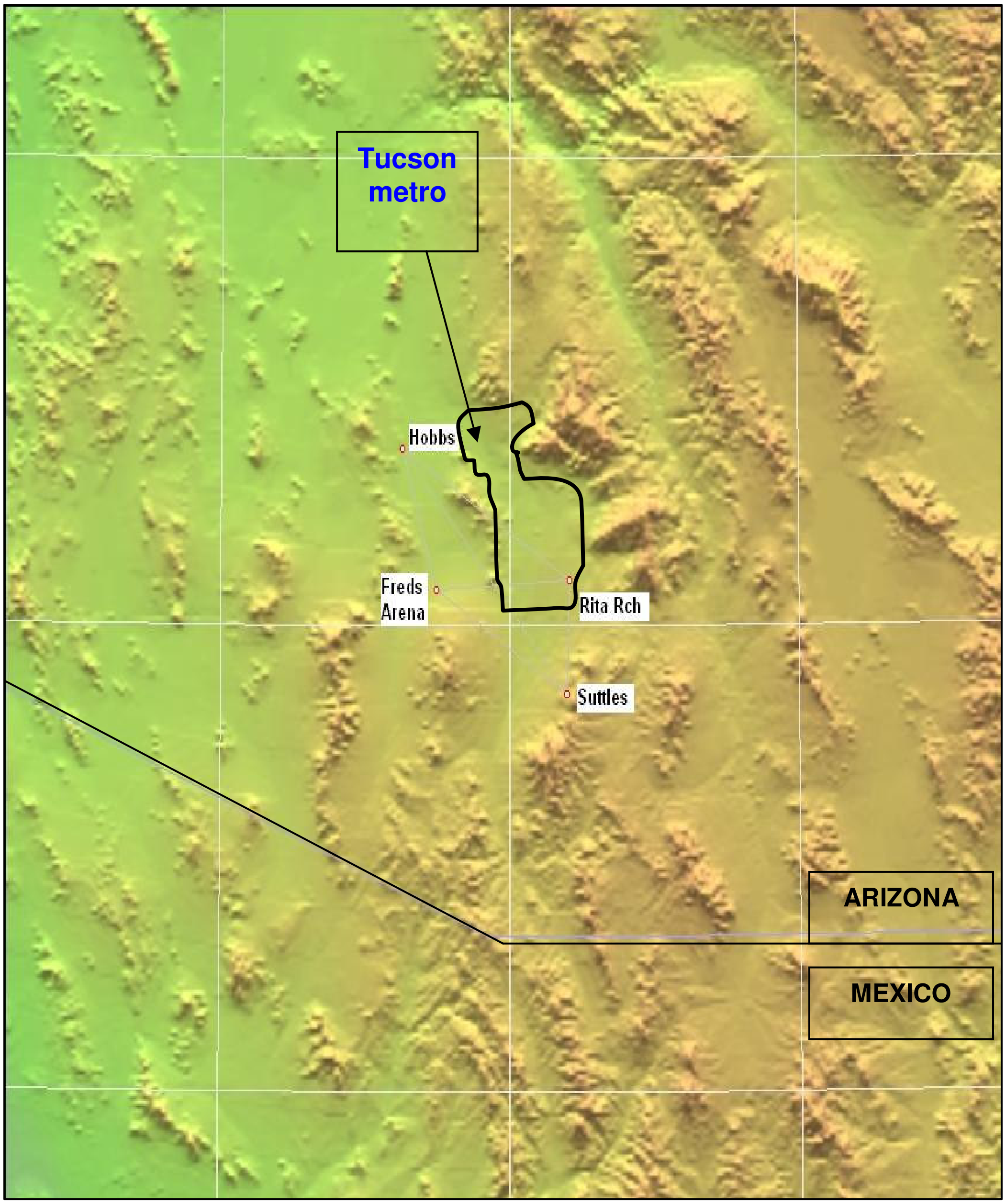


Figure 3: Layout of the Tucson LS8000 network. Sensor locations labeled and shown by red circles.

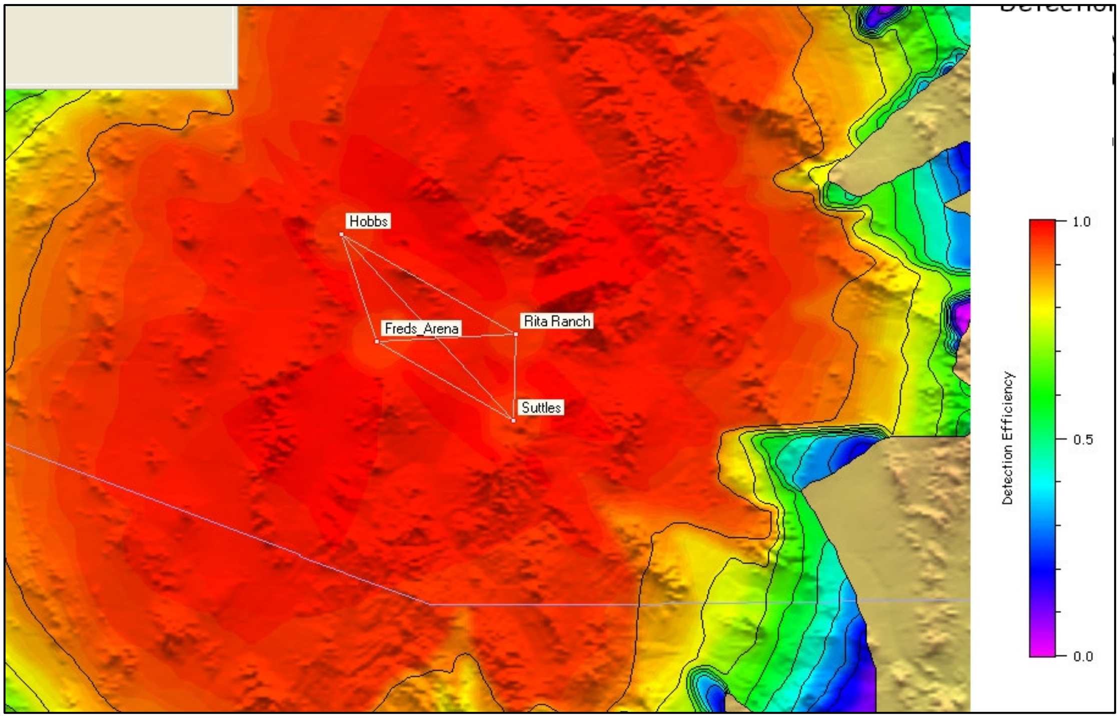


Figure 4: Estimated total lightning flash detection efficiency of the LS8000 network. Color scale on the right goes from 0.0 to 1.0 (100%).

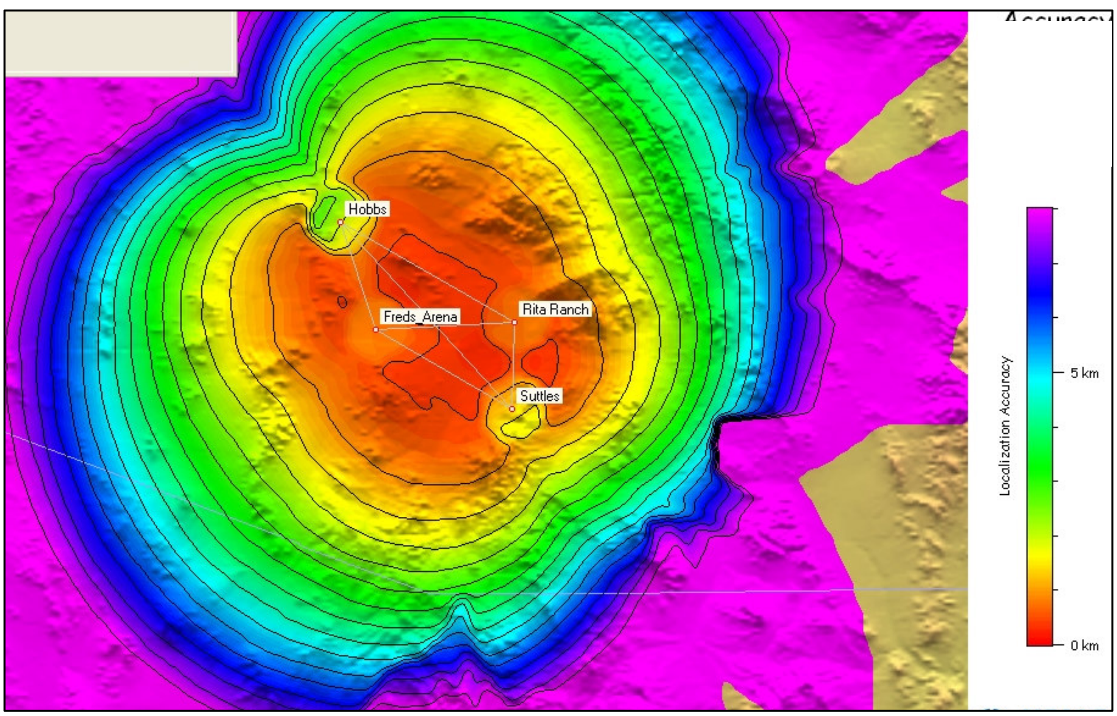


Figure 5: Estimated location accuracy of the LS8000 network. Color scale on the right goes from 0.0 to 8.0 km.

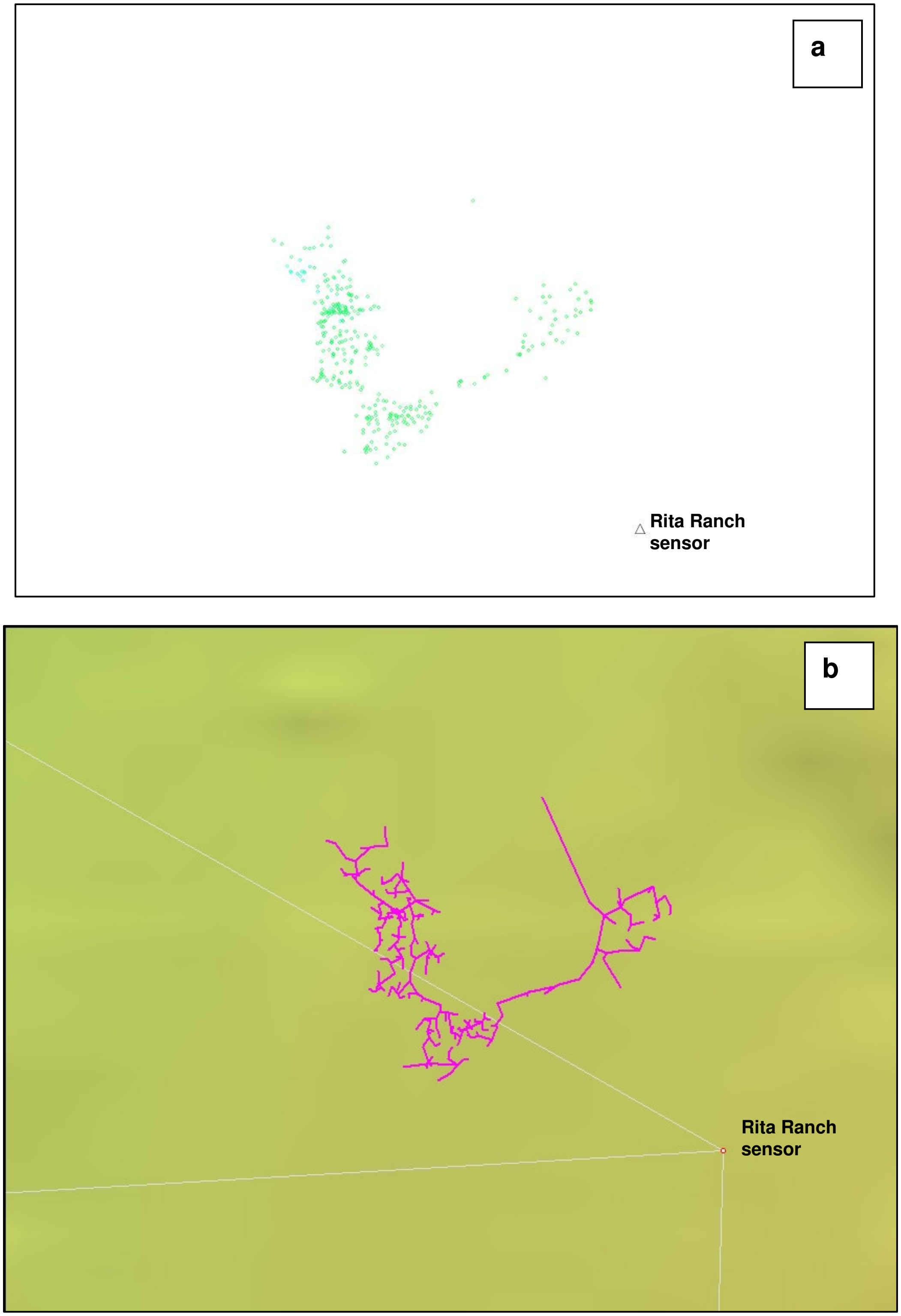


Figure 6: Close-up view of a large flash observed near the Rita Ranch sensor in the Tucson LS8000 network. (a) Individual VHF emissions located by the network. (b) after processing by flash algorithm.

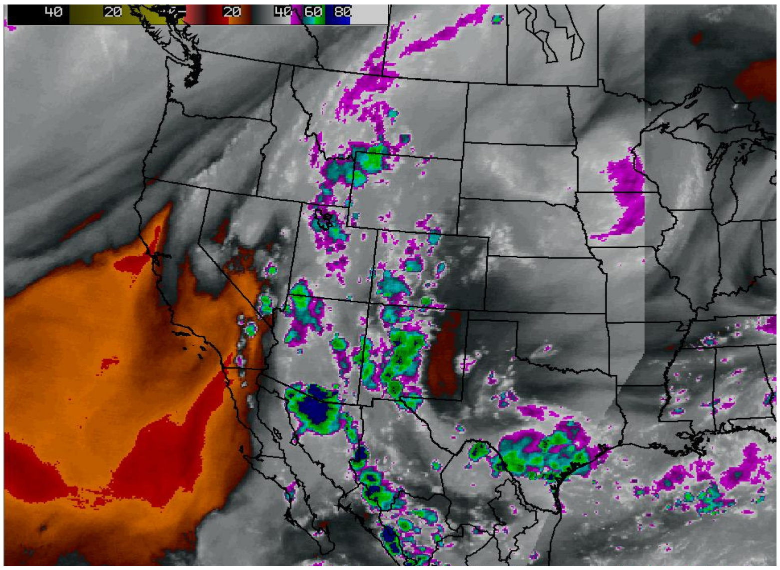


Figure 7: Water vapor satellite imagery, 23:00 UTC 24 July 2007.

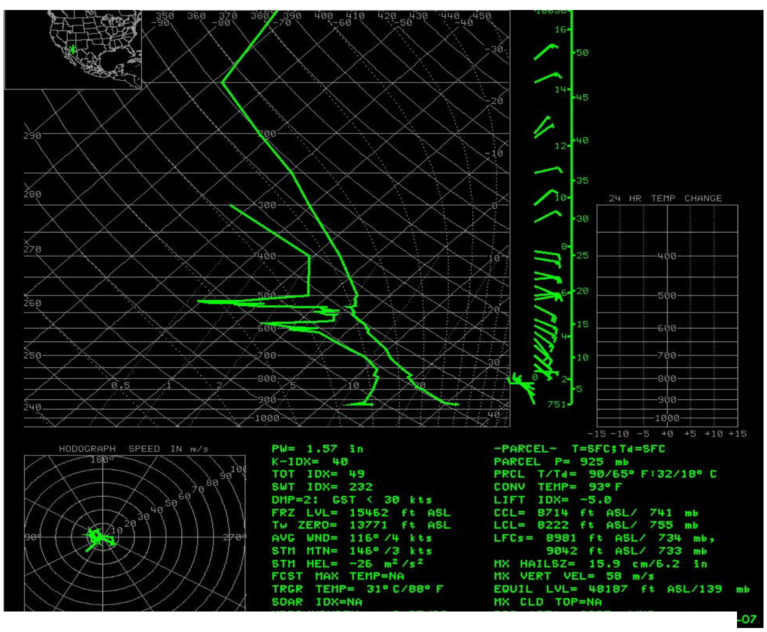


Figure 8: Skew-T/Log-P, NWS Tucson upper air sounding, 00:00 UTC 25 July 2007. Winds are in kts.

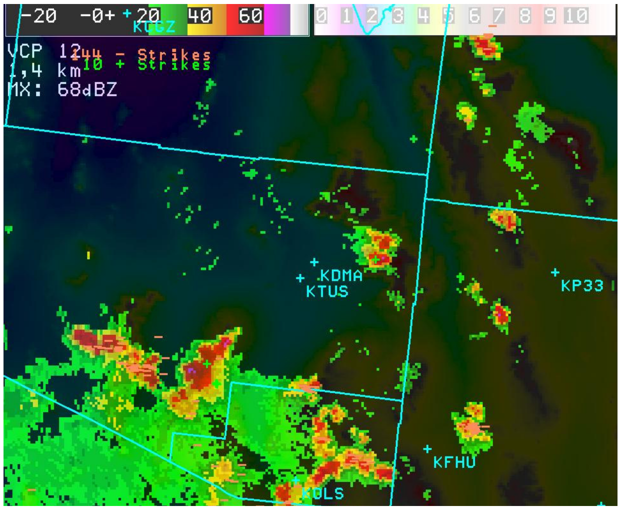


Figure 9: Composite reflectivity from WDR-88D KEMX Radar, and National Lightning Detection Network (NLDN) positive (green plus symbols) and negative (orange minus symbols) CG lightning strike data, 22:00 UTC 24 July. KTUS marks the location of Tucson International Airport.

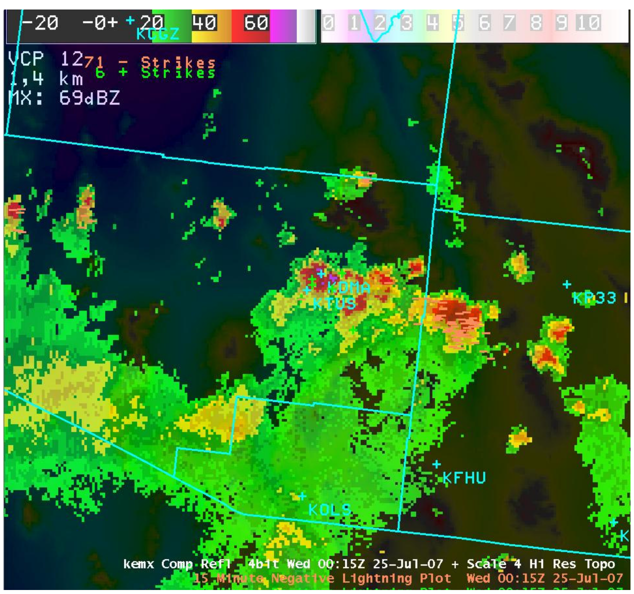


Figure 10: Same as Figure 9, except for 00:15 UTC 25 July. Multiple wind damage reports were received 00:15-00:30 UTC over central Tucson.

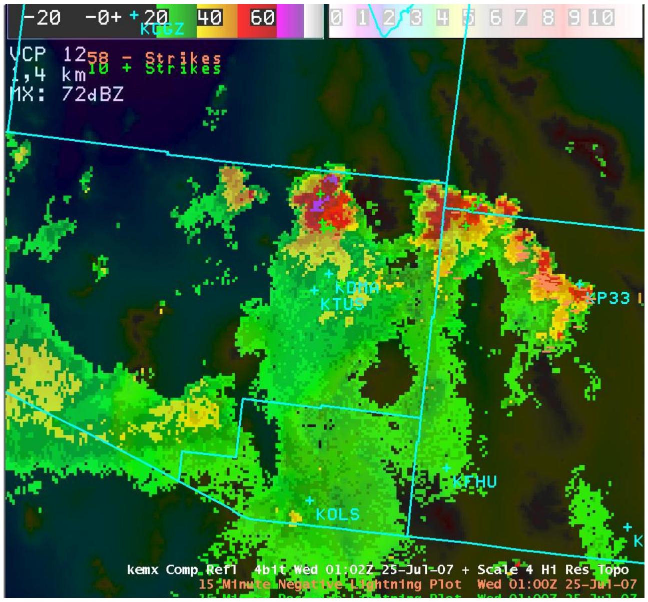


Figure 11: Same as Figure 9, except for 01:00 UTC 25 July.

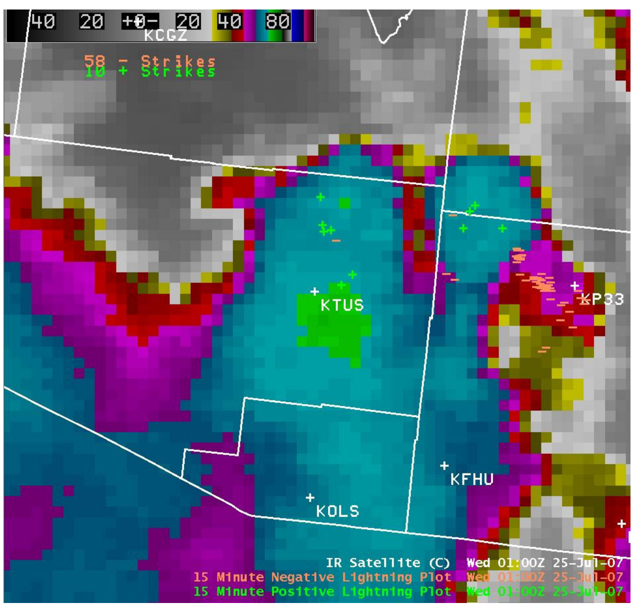


Figure 12: Infrared satellite imagery over Tucson Metro Area, along with NLDN 15-minute lightning data, 01:00 UTC 25 July.

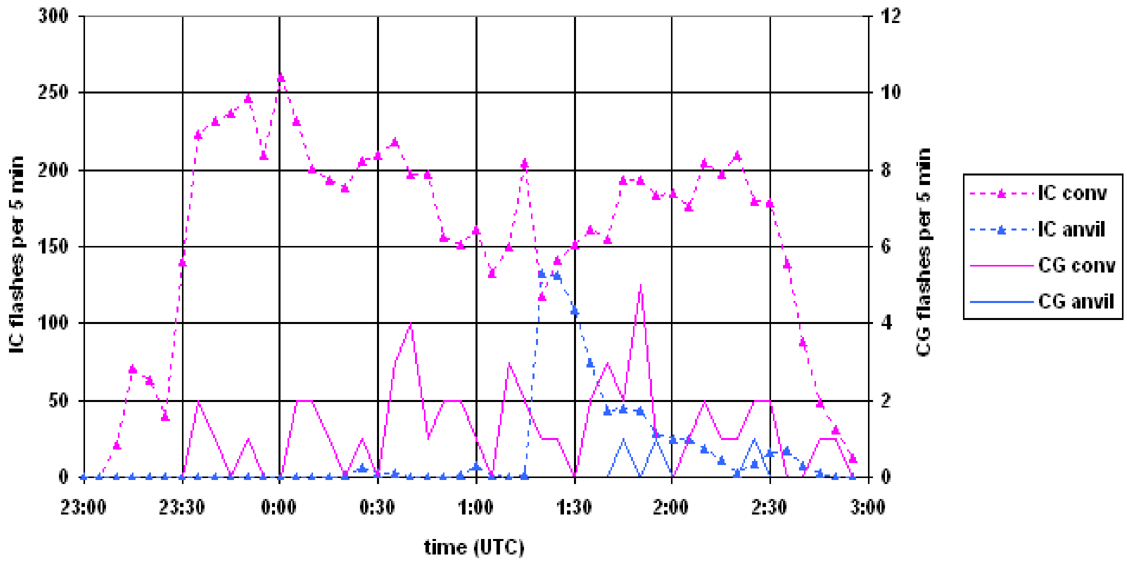


Figure 13: Total cloud and cloud-to-ground lightning comparison, between the leading convection (conv) and training (anvil) portion of the MCS. Time series from 23:00 UTC 24 July through 03:00 UTC 25 July. Note the scale difference between cloud (left) and CG flashes (right).

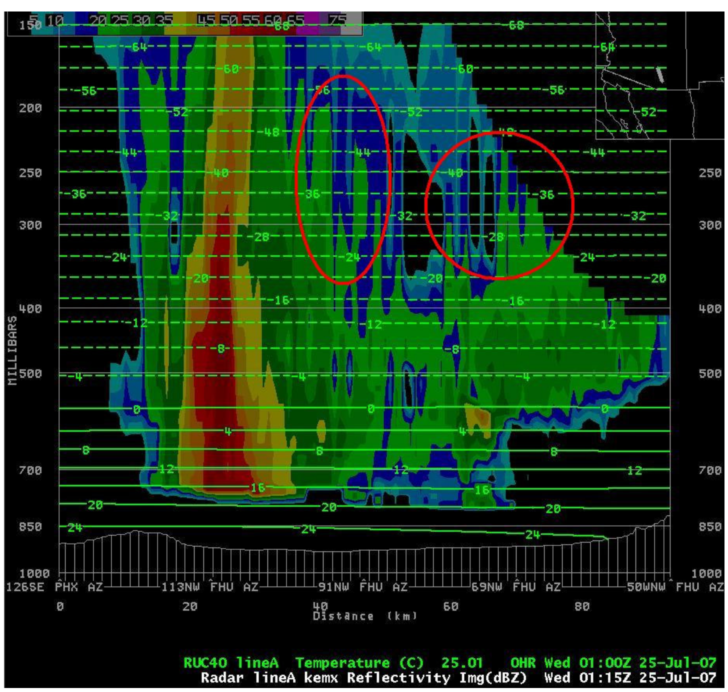


Figure 14: Reflectivity cross section with KEMX WSR-88D data 01:15 UTC 25 July; Rapid Update Cycle (RUC) temperatures, valid 01:00 UTC 25 July. Cross section runs from the far northwest side of Tucson (left) to 15 miles north of Nogales, Arizona (right). Secondary anvil towers are circled.

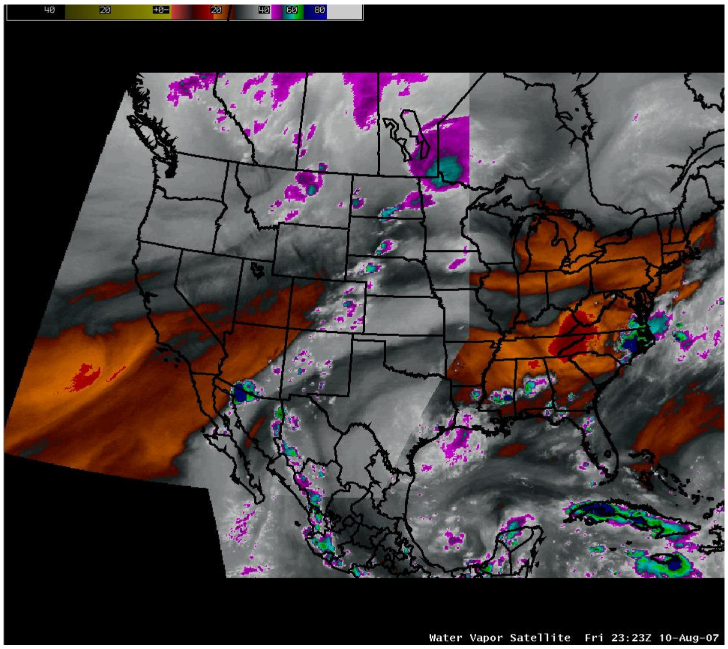


Figure 15: Water vapor satellite imagery, 23:23 UTC 10 August 2007.

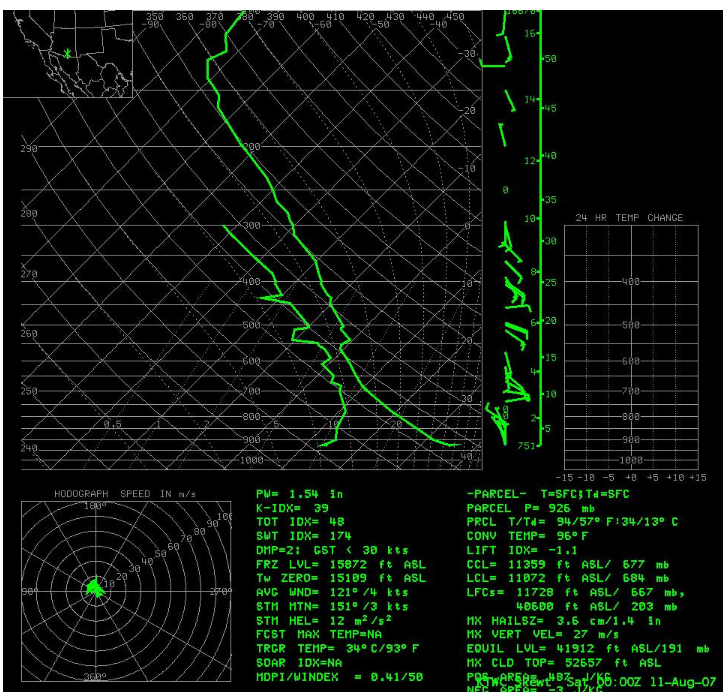


Figure 16: Skew-T/Log-P, NWS Tucson upper air sounding, 00:00 UTC 11 August 2007. Winds are in kts.

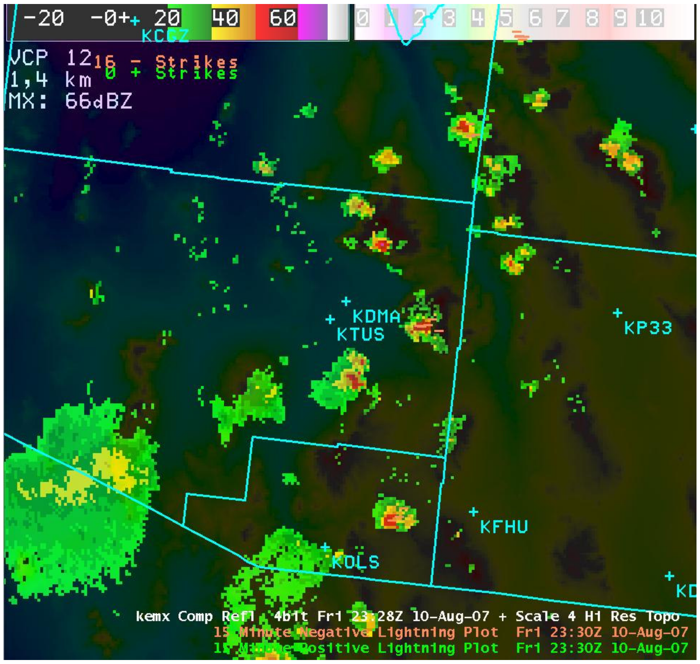


Figure 17: Same as Figure 9, except for 23:30 UTC 10 August 2007.

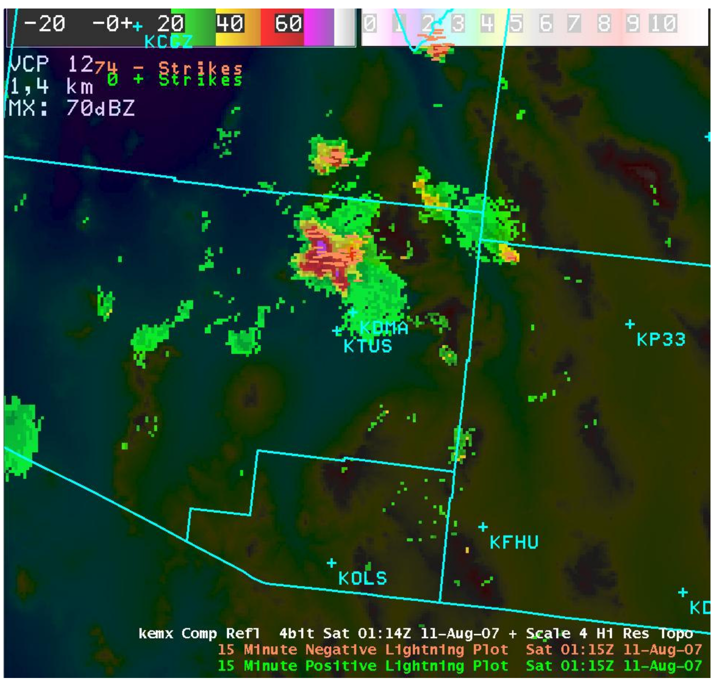


Figure 18: Same as Figure 9, except 01:15 UTC 11 August 2007. The first severe hail (>2cm diameter) was reported under the cell at 01:20 UTC.

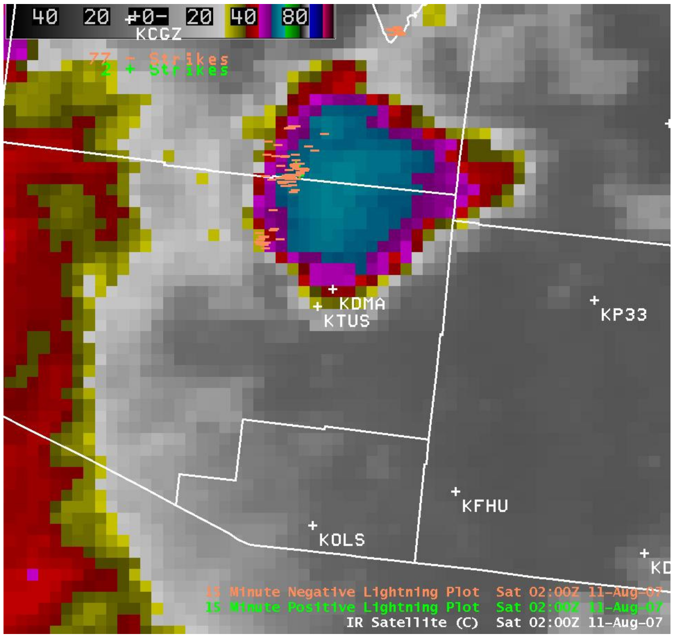


Figure 19: Same as Figure 12, except for 02:00 UTC 11 August 2007.

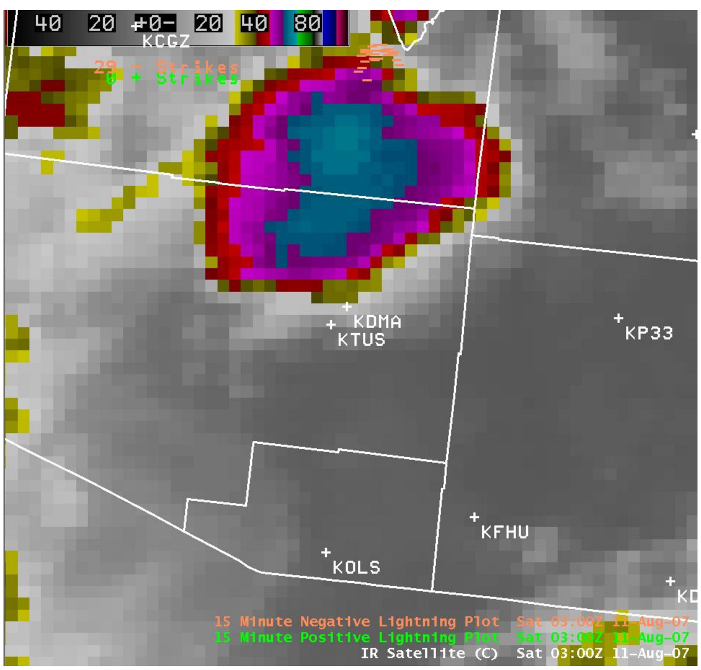


Figure 20: Same as Figure 12, except for 03:00 UTC 11 August 2007.

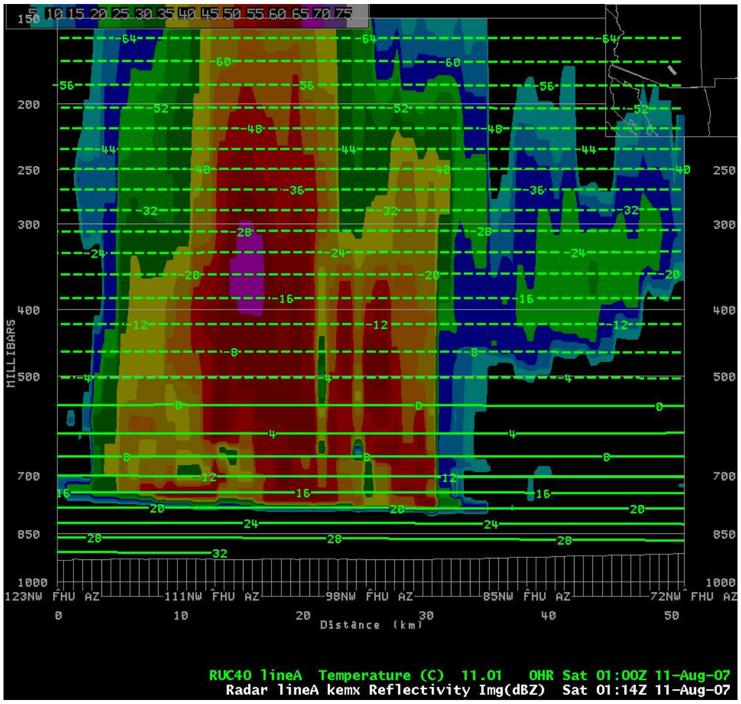


Figure 21: Reflectivity cross section 01:14 UTC 11 August; Rapid Update Cycle (RUC) temperatures, valid 01:00 UTC 11 August. Cross section runs from the far northwest side of Tucson (left) to central Tucson (right).

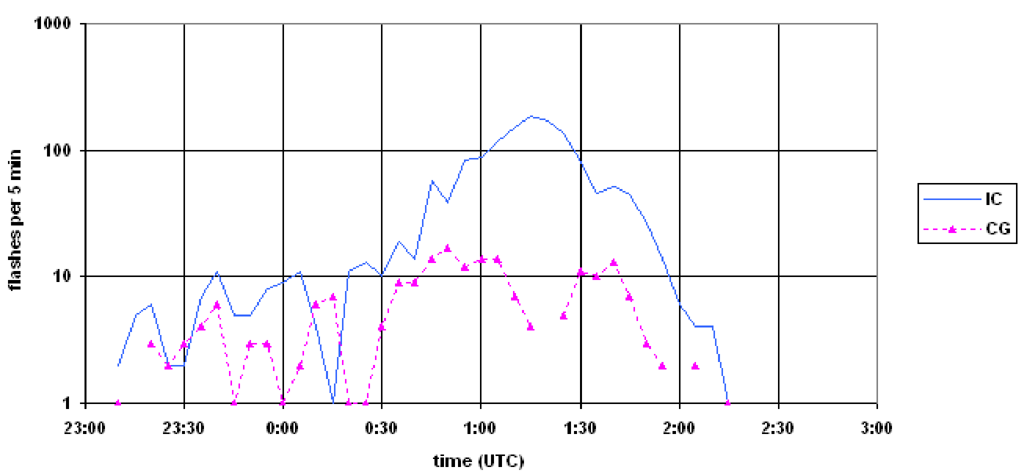


Figure 22: Total cloud and cloud-to-ground flash densities, 23:00 UTC 10 Aug through 03:00 UTC 11 Aug.