# ALMA Memo No. 487
# Lightning Near Cerro Chascón

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**Abstract**

We present a preliminary analysis of the spatial and seasonal lightning distribution near the Cerro Chascón science preserve, probed with a space-borne imaging sensor and ground-based storm detectors. The lightning flash rate in this area is among the lowest in the world for comparable latitudes. Thunderstorms only occur around 5 days per year. Most observed lightning strikes occurred far to the east of Cerro Chascón, in Bolivia and Argentina. Lightning was detected primarily during the summer (December–March), particularly in the afternoon and evening (UT = 16h–1h). Morning (UT = 10h–14h) events were rare. There seem to be two types of storms — heavy storms from the west, and milder, but more common, storms from the east. No significant difference was found between the strike rates at Pampa La Bola and at Llano de Chajnantor.

## 1 Introduction

Lightning poses a natural threat to the ALMA. The array site in the Cerro Chascón science preserve is very flat without any trees or tall structures other than the array itself. Hence the $\approx$ 15 m high antennas risk being struck by lightning if the weather is stormy. Radio telescopes can be substantially damaged by lightning. At the Nobeyama Radio Observatory, the 45 m radio telescope was struck by lightning on 1994 August 30 and, despite a lightning protection system, the telescope electronics were severely damaged. The repair cost was significant ($\approx$ 180000 USD) and the common-use program was interrupted for two months.

Since 1995 April, when NRAO first installed atmospheric monitoring equipment in the area, there have been two incidents of equipment damage possibly caused by lightning. Over several days at the end of 2000 January, the power inverter failed in the ESO equipment container on Llano de Chajnantor and the power supplies failed in three computers in the adjacent, but electrically isolated, NRAO container. Other computers and instruments in those containers were unaffected. In 2001 January–February, the Gunn diode oscillator of the 220 GHz radiometer, the power regulator of the two channel IF converter of the site testing interferometer, and the power regulators of the high response anemometer failed in the NRO equipment containers at Pampa La Bola. Although the exact reasons for these failures remain unknown, lightning seems a likely explanation – if not a direct strike, then surge currents induced by a nearby strike.

Two incidents in nine years suggest we should not dismiss lightly the lightning threat in this area. Moreover, if the array is in its most compact configuration, even a single lightning strike might damage a significant fraction of the array elements, since effective grounding seems difficult and costly because of the high soil resistivity near the surface [1–3]. In addition to the direct threat of equipment damage, lightning poses a threat to the safety of workers at the array during ALMA construction and operation. To address these risks adequately, therefore, the properties of thunderstorms in the area, including their frequency, their spatial and seasonal distribution, and their movement, must be understood. Lightning discharge number per minute, percentage of cloud-to-ground discharges, multiplicity, inter-stroke time interval, and continuous current of storms were studied in the first report [4]. Here we present an analysis of the spatial and seasonal lightning distribution near Cerro Chascón, probed with a space-borne imaging sensor and two ground-based storm detectors.

## 2 Instruments and Data

### 2.1 Lightning Image Sensor

The global spatial lightning distribution was examined with archived data from the Lightning Image Sensor (LIS) [5] aboard the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched on 1997 November 28 from the Tanegashima Space Center in Japan. The LIS is a staring imager optimized to locate and detect lightning with storm-scale resolution (4–7 km) over a large region (600 km $\times$ 600 km) of the Earth's surface. As the TRMM orbits the Earth, its sub-satellite point travels 7 km s$^{-1}$ so the LIS can observe a point on the Earth or a cloud for almost 90 s as the satellite passes overhead. Despite the brief duration of an observation, it is long enough to estimate the flash rate of most storms. The instrument records the time of occurrence, the radiant energy, and the location of lightning flashes within its field-of-view. A Real Time Event Processor determines when a lightning flash occurs, even in the presence of bright sunlit clouds, enabling the system to detect weak lightning and achieve a 90% detection efficiency. Because the TRMM orbit has an inclination of 35°, the LIS only covers latitudes between 35° N and 35° S.

Although the LIS only views a point on the Earth every a few weeks so the time sampling is incomplete, the data are unbiased and extensive so the ensemble of the data collected with this instrument faithfully reflects the spatial lightning distribution. Annual and seasonal composite lightning distributions of quality controlled data are readily available [5]. The surface density of detected flashes roughly follows the keraunic level, which is the number of days per year with thunderstorms, with a scaling of $\sim 0.2$ days (flash scale)$^{-1}$.

### 2.2 Storm Detectors

Direct measurements of thunderstorms were made with two different storm detectors. A Boltek StormTracker [6] was installed on the NRAO container at Llano de Chajnantor on 1999 November 9. It detects low frequency radio bursts from lightning with crossed ferrite loop antennas. Its sensible range is 480 km. This type of small detector may perform better for distant events than for nearby events because of the gain pattern of the loop antennas. Measurements were made from 1999 November 9 to 2000 January 27 and from 2000 June 8 to 2001 June 12. Individual strike times were logged in UT with a precision of 2 s.

A Technocrat 22-DV storm detector recorded the spatial distribution of lightning within 160 km of the NRO containers at Pampa La Bola. Because this instrument requires substantial electric power (500 W at maximum), it was operated only on a temporary basis starting from 2000 February 4. The data were recorded every 15 minutes referred to local civil time without summer correction (UT − 4h). The specified detection rate is about 95% and the specified accuracy is ±1.5 km in distance and ±1.5 km in direction at a range of 40 km[1].

Both of these instruments use loop antennas and dual-frequency delay monitors to locate the direction and distance of lightning strikes, so cloud-to-ground and cloud-to-cloud flashes cannot be distinguished[2]. Furthermore, the response patterns of the loop antennas can introduce a 180° ambiguity in the measured direction and also cause difficulties in locating nearby events (within $\sim$ 100 km in the case of the StormTracker). Diagonal NW–SE and NE–SW patterns in the StormTracker data are apparent artifacts of nulls in the antenna response patterns.

# 3 Results and Discussion

## 3.1 Spatial Lightning Distribution

The flash density in northern Chile is among the lowest in the world for this latitude (Figures 1–2). The keraunic level is around 5 days, which is lower than for most higher latitude regions in Japan, Europe, or North America (10–40 days).

LIS data over six years for a 900 km × 920 km region near Cerro Chascón were summarized monthly (Figure 3). Although the LIS time sampling is incomplete, the data provide a face-on view of the spatial lightning distribution with high accuracy, unambiguous positioning with a spatial resolution of 4–7 km. Lightning flashes occurred predominantly to the east of Cerro Chascón, often far into Bolivia and Argentina. The lightning distribution's rather sharp western edge closely follows the crest of the Andes. Even closer view of the LIS events over six years near Cerro Chascón is shown in Figure 4. Both Pampa La Bola (22.96° S, 67.70° W) and Llano de Chajnantor (23.02° S, 67.76° W) are included in this area. The lightning events spread over the area and no distinguishable trend in spatial distribution exists.

On this smaller scales, the spatial distribution was evaluated with the StormTracker data for a shorter period but with much denser sampling (Figures 5–6). Note ghost images and artificial diagonal patterns are sometimes apparent. Aside from these artifacts, the spatial distribution is consistent with the features of the LIS data. Because it operated continuously, the StormTracker successfully recorded strikes near Cerro Chascón in 2000 January.

The small scale distribution was independently measured with the data from the Technocrat storm detector (Figures 7–9). This instrument follows spatial distribution of nearby ($<$ 160 km) events more closely. The daily maximum number of events per 5 minutes, which indicates activity of storm clouds, is also shown in the figure. The basic appearance of the distribution agrees with the LIS and StormTracker data. In addition, this closer view of the spatial lightning distribution with information of lightning activity reveals two types of nearby storms — heavy storms to the west and milder, but more common, ones to the east. The ALMA site lies near the ridge separating the heavy western storms from the milder eastern ones. The orographic uplift associated with the western slope may in part explain the enhanced activity of the storms to the west.

With the above data sets, we found no evidence so far that supports difference in the strike rates at Pampa La Bola and at Llano de Chajnantor. Given that instruments at Pampa La Bola and Llano de Chajnantor sites have both experienced failures probably due to lightning, adequate lightning protection/prevention system is required irrespective of the location in this area.

[1] The distance accuracy seems poorer than the specified value for nearby events. See Figure 7.

[2] For storms recorded in 2002–2003 at Pampa La Bola, the occurrence percentage of cloud-to-ground discharges was 66%.

### 3.2 Seasonal and Diurnal Variation of Lightning Rate

Information on seasonal and diurnal distribution of lightning rate is of particular interest in scheduling of outdoor works. Lightning flashes detected by the LIS from 1998 January to 2003 December in the $0.5^\circ \times 1.0^\circ$ (56 km × 102 km) area centered at 23.0° S and 67.5° W are listed in Tables 1–2. Note the LIS time sampling is incomplete, so the data for this area on 2000 January 27, when equipments at Llano de Chajnantor were damaged, is missing from this list. Although the number of events is limited, these data (Figure 3; Tables 1–2) suggest lightning in the immediate vicinity of Cerro Chascón is very rare and occurs primarily during summer (January–March) evenings. This picture is consistent with our limited experience at the site.

The diurnal and seasonal lightning distributions were also determined with denser time sampling from the StormTracker data (Figure 10). These data confirm the scenario suggested by the LIS data. Lightning was recorded chiefly during summer afternoons and evenings (UT = 16h–1h; Figure 12). Although significant lightning strikes occurred during July–November (Figure 11), these strikes were distant (Figures 5–6). Morning (UT = 10h–14h) events were relatively rare. In particular, at dawn, the strike rate drops abruptly (Figure 12). During 2000, the average diurnal variation was about three times smaller than the seasonal variation.

The diurnal and seasonal variation of the rate of nearby ($< 160$ km) lightning was measured with the Technocrat 22-DV storm detector (Figure 13). Although only a small number of nearby events were recorded, the data confirmed that the nearby lightning also occurs mostly in the afternoon and evening (UT = 16h–1h) with no major events at other times.

### 3.3 Storm Motion and Hailstone

Knowing how storms move is important, e. g., for effectively locating lightning rods upwind of a cluster of antennas. Storm motion may be also reflected in a local variation of the lightning risk. This is expected from the physics of charging in storm clouds. As particles within a cloud, or hydrometeors, grow and interact, some become charged, possibly through collisions. Smaller particles tend to acquire positive charges, while larger particles acquire negative charges. These particles then separate under the influences of updrafts and gravity until the cloud tops acquire net positive charges and the cloud bases become negatively charged. After a cloud passes over a mountain peak, the updrafts may calm down, reducing the risk of a lightning strike. Thus, lightning should be closely related to the existence of updrafts, which reflect local topography and storm motion.

Storm motion on a large scale was followed with the StormTracker data for the first eight days of 2000 January (Figure 14). Storm motion on a smaller scale was followed with the Technocrat data (Figure 15). The heavy storms arise near Salar de Atacama and sometimes move eastbound to the site. The milder, but more common storms come from the east, beyond the Bolivian border. The storm motion traced by lightning events appears uncorrelated with the surface wind direction, which is predominantly west to east, partly because of limited accuracy of the present sets of lightning detectors. Further studies with twin sets of electromagnetic antennas used in previous report [4] is foreseen to address this issue.

According to our experience at the site, nearby lightning often follows hailstone ($\sim 4$ mm diameter). Hailstone is thus used as alert of lightning hazard to outdoor workers who are often not equipped with information from modern lightning detectors.

## 4 Summary

Data from three instruments show lightning near Cerro Chascón is uncommon. The keraunic level is around 5 days, among the lowest in the world land for comparable latitudes. Lightning strikes occur during summer (December–March) afternoons and evenings (UT = 16h–1h).

Strikes during other seasons or the morning (UT = 10h–14h) are rare. Two classes of storms were identified: the heavy storms coming from the west, and the milder, but more common ones coming from the east. The array site lies near the ridge that separates the heavy western storms and the milder eastern ones.

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## References

[1] Sakamoto, S., Ezawa, H., Takahashi, T., & Yamaguchi, N. 2000, "Vertical profile of soil resistivity at Pampa La Bola and Llano de Chajnantor locations," ALMA Memo 326

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[5] `http://thunder.msfc.nasa.gov/lis/`

[6] `http://www.boltek.com/`

[7] United States Air Force 1960, "Handbook of Geophysics, Revised Edition," (New York: Macmillan)

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[9] Sakamoto, S., Handa, K., Kohno, K., Nakai, N., Otárola, A., Radford, S. J. E., Butler, B., & Bronfman, L. 2000, "Comparison of meteorological data at the Pampa La Bola and Llano de Chajnantor sites," ALMA Memo 322

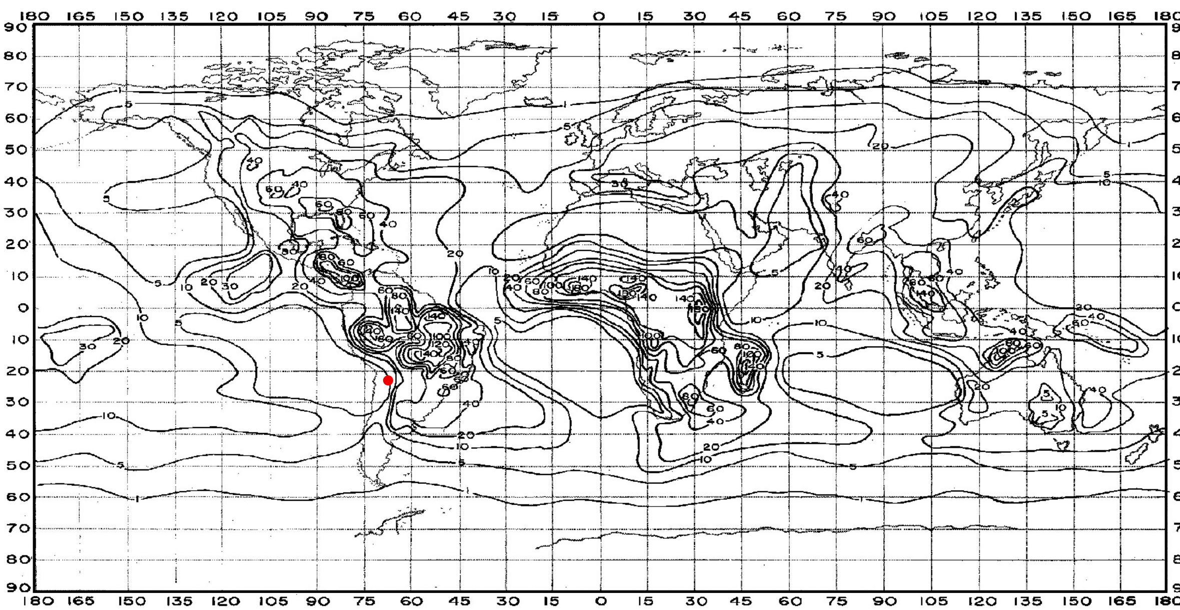



Figure 1: Location of the ALMA site (*red dot*) overlaid on a map of keraunic levels, or the number of the days per year with thunderstorms, throughout the world for the entire year [7]. The aspect ratio of the original map has been modified. Near Cerro Chascón, 23.0° S, 67.7° W, the keraunic level is around 5 days.

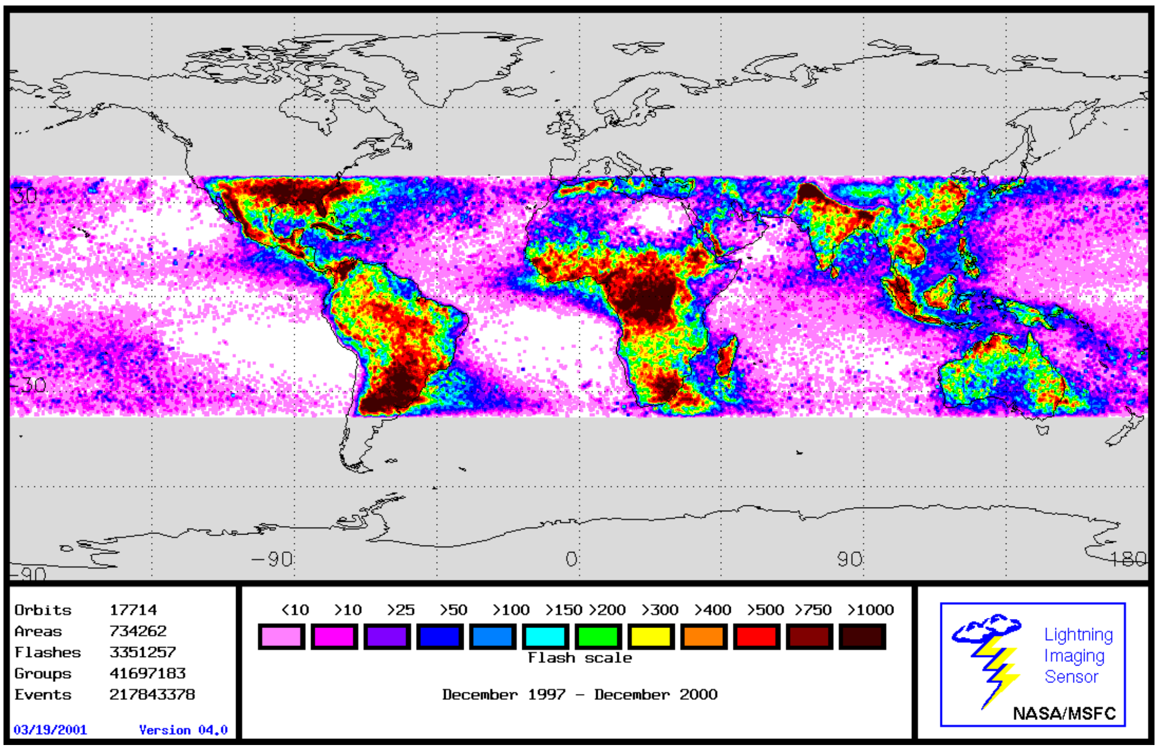



Figure 2: Global spatial lightning distribution recorded by the Lightning Image Sensor (LIS) [5] aboard the TRMM satellite. The measurements span 1997 December to 2000 December and covers latitudes between 35° N and 35° S.

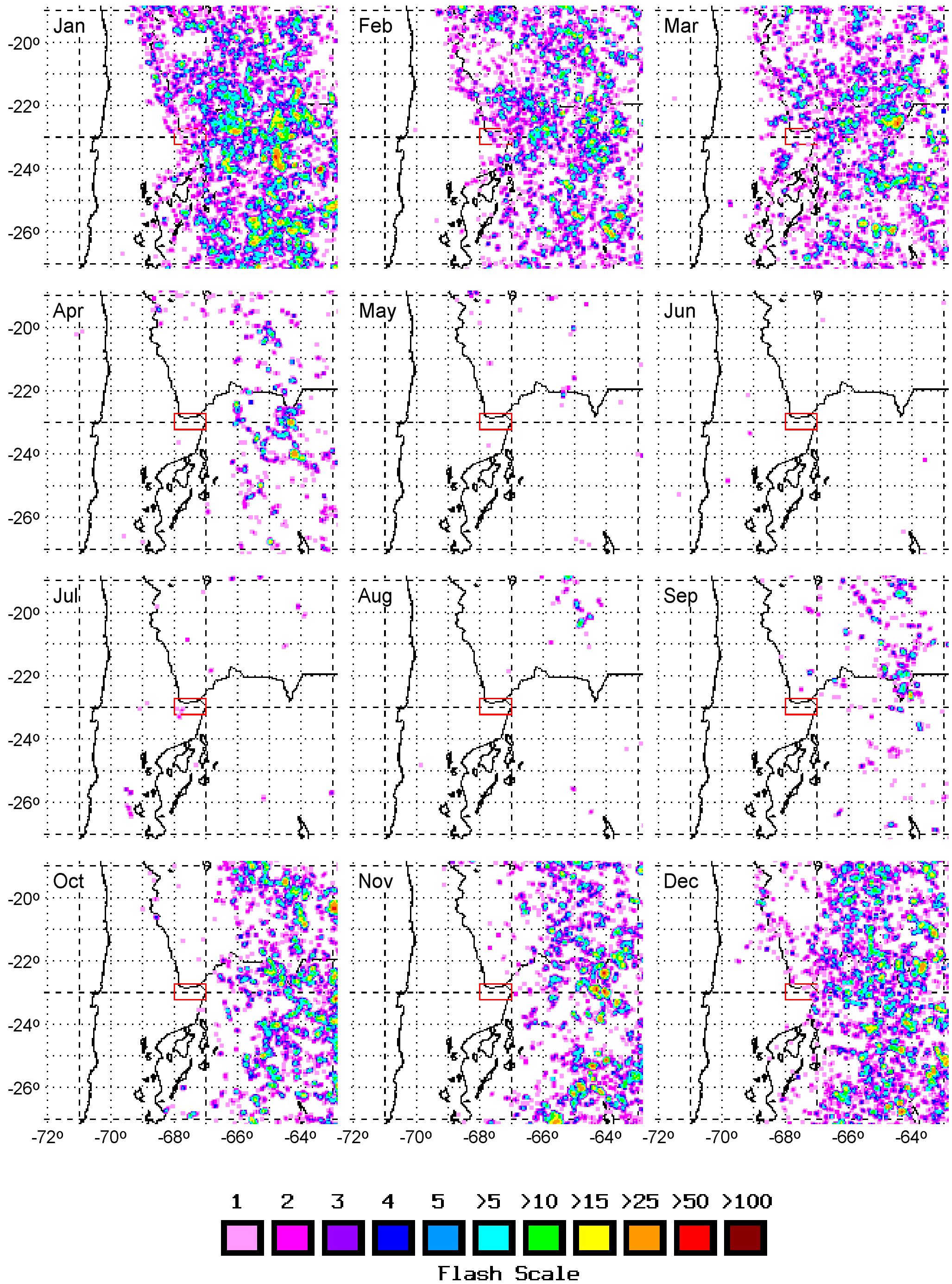



Figure 3: Monthly spatial lightning distributions recorded by the Lightning Image Sensor (LIS) [5] over a $8^\circ \times 9^\circ$ (900 km × 920 km) region of northern Chile. The distributions were synthesized by summing up data for each month from 1998 January to 2003 December (six years). The mesh is $1.0^\circ \times 1.0^\circ$. The red rectangle in the middle of each panel indicates a $0.5^\circ \times 1.0^\circ$ area (56 km × 102 km) centered at $23.0^\circ$ S and $67.5^\circ$ W, for which all events recorded by LIS are listed in Table 1. Note the time sampling is incomplete.

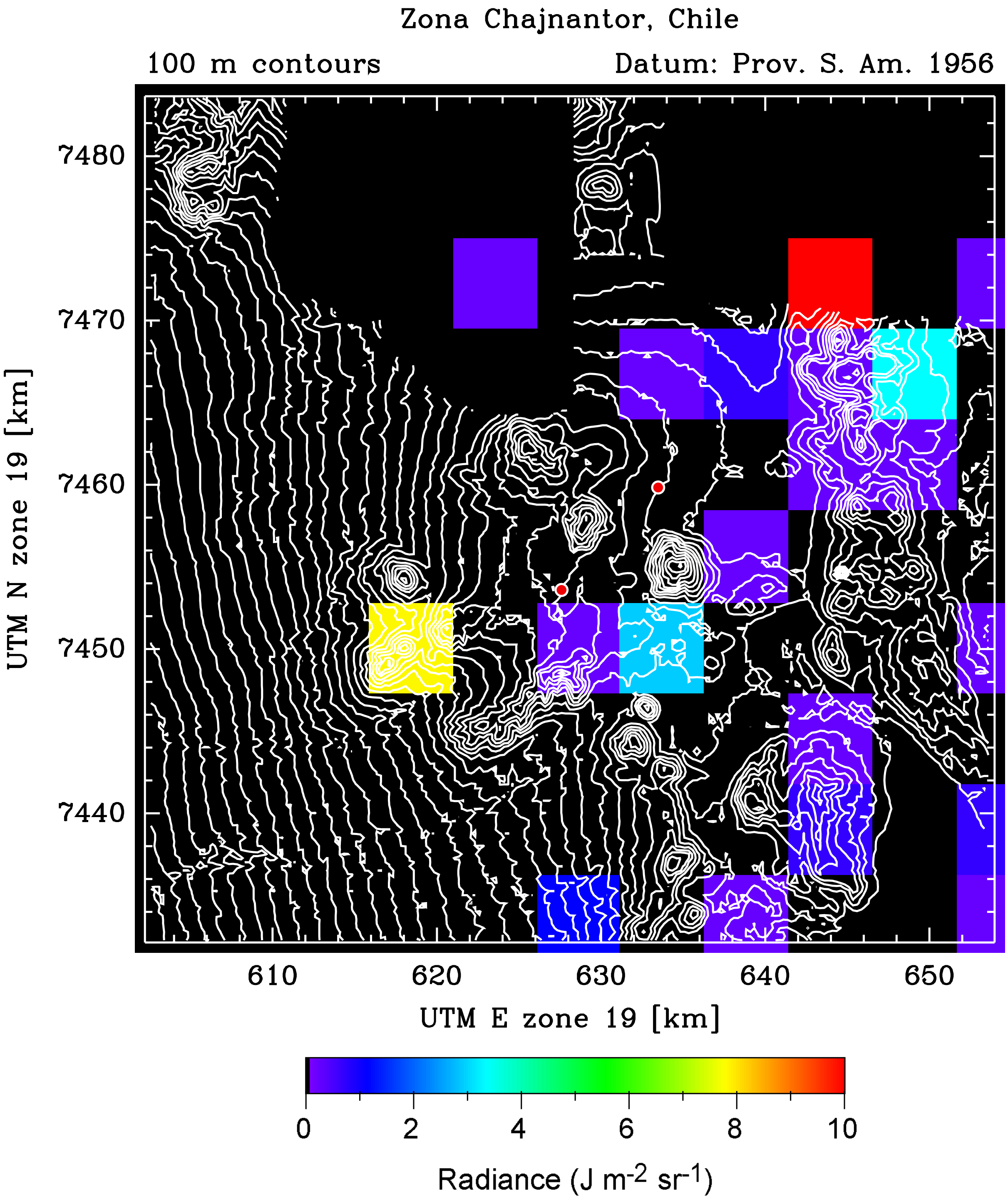



Figure 4: LIS events over six years near Cerro Chascón. Contour map is based on the data digitized in 2001 by Sistemas Gráficos, Geográficos, y Mineros Ltda., Antofagasta, from maps published by the Instituto Geográphico Militar de Chile. Filled red circles indicate Pampa La Bola (*upper right*, 4800 m) and Llano de Chajnantor (*lower left*, 5050 m) sites.

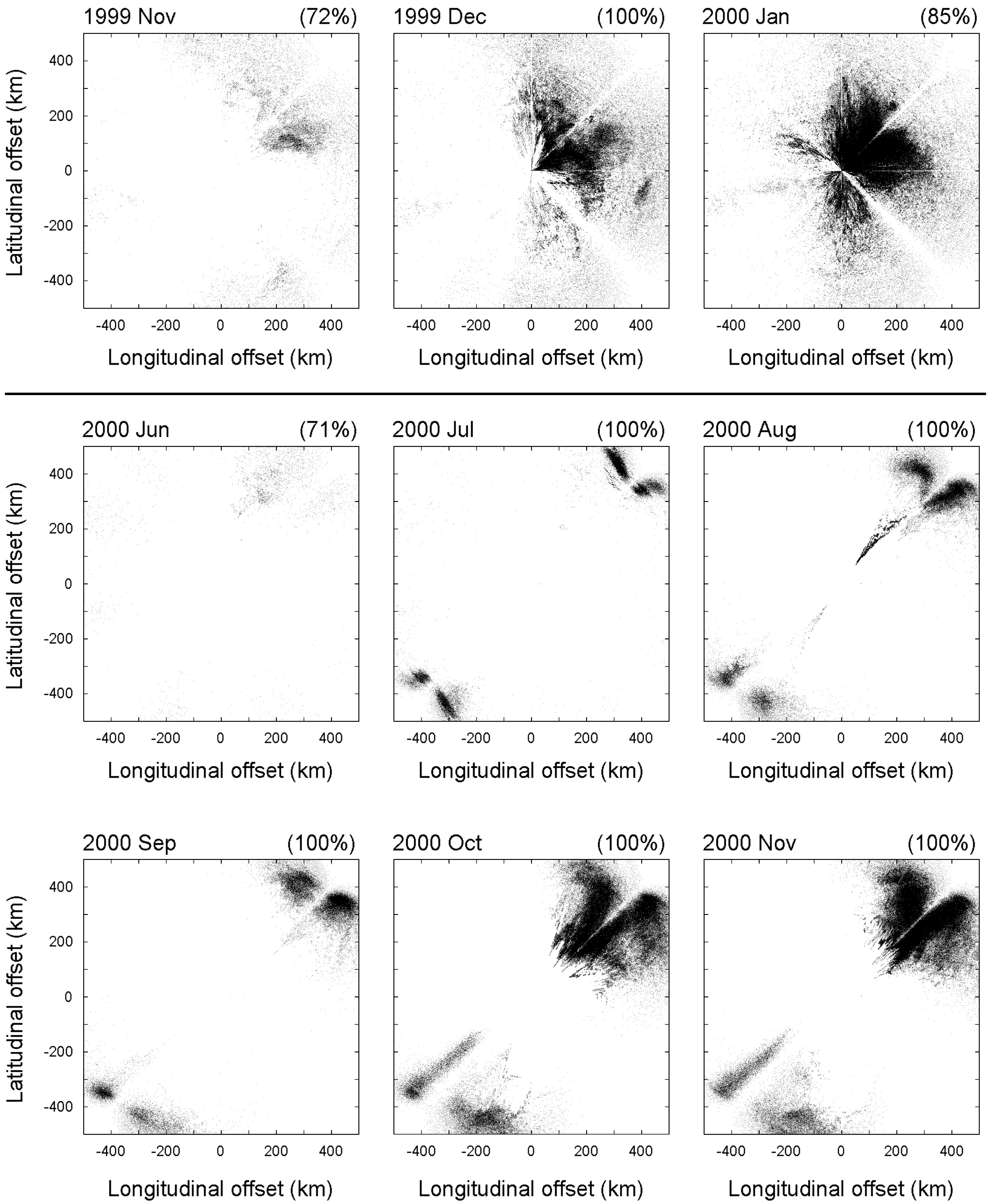



Figure 5: Monthly spatial lightning distributions recorded by the Boltek StormTracker. The coordinates are offsets from the NRAO/ESO containers on Llano de Chajnantor. Each dot represents one lightning strike. Ghost images due to the 180° ambiguity of the loop antenna are apparent. Diagonal features are artifacts of nulls in the antenna response patterns. At the top of each panel, the fraction of time when the instrument was running is indicated in parentheses.

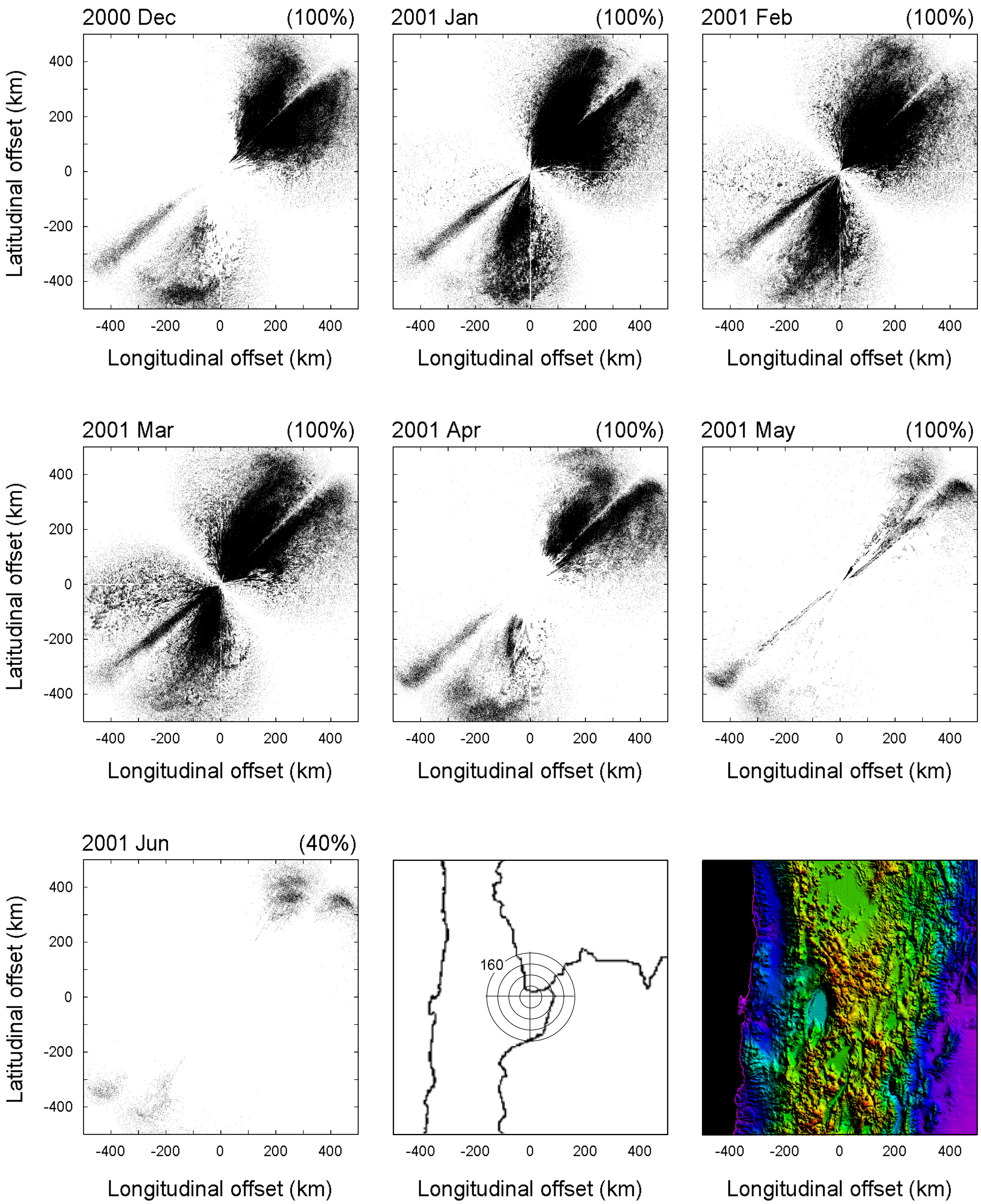



Figure 6: Same as Figure 5. The 160 km radius area of the Technocrat storm detector overlaid on the coast line and borders, as well as a digital elevation model image of the same area [8], are shown at the bottom.

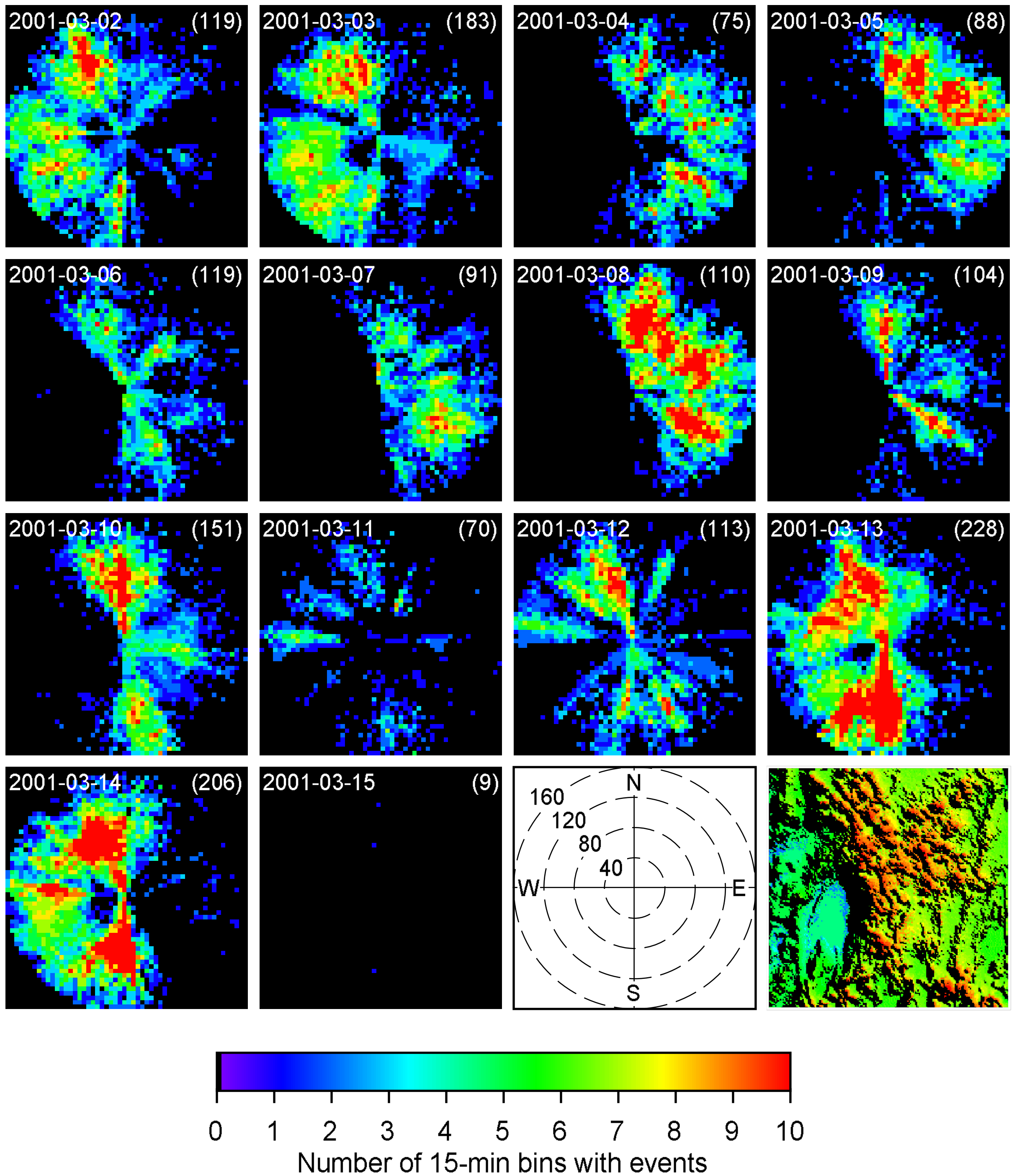



Figure 7: Spatial distribution of lightning recorded by the Technocrat storm detector in 2001 March 2–15. Coordinates are offsets from the NRO containers on Pampa La Bola. The color codes the number of 15-minutes bins with strikes recorded each day in each 10 km × 10 km area. The concentric rings have radii of 40, 80, 120, and 160 km. At the top of each panel, the daily maximum number of events per 5 minutes, which indicates activity of storm clouds, is shown in parentheses. See Figure 13 for the period when the instrument was operating. The bottom right panel shows a digital elevation model image of the same area [8].

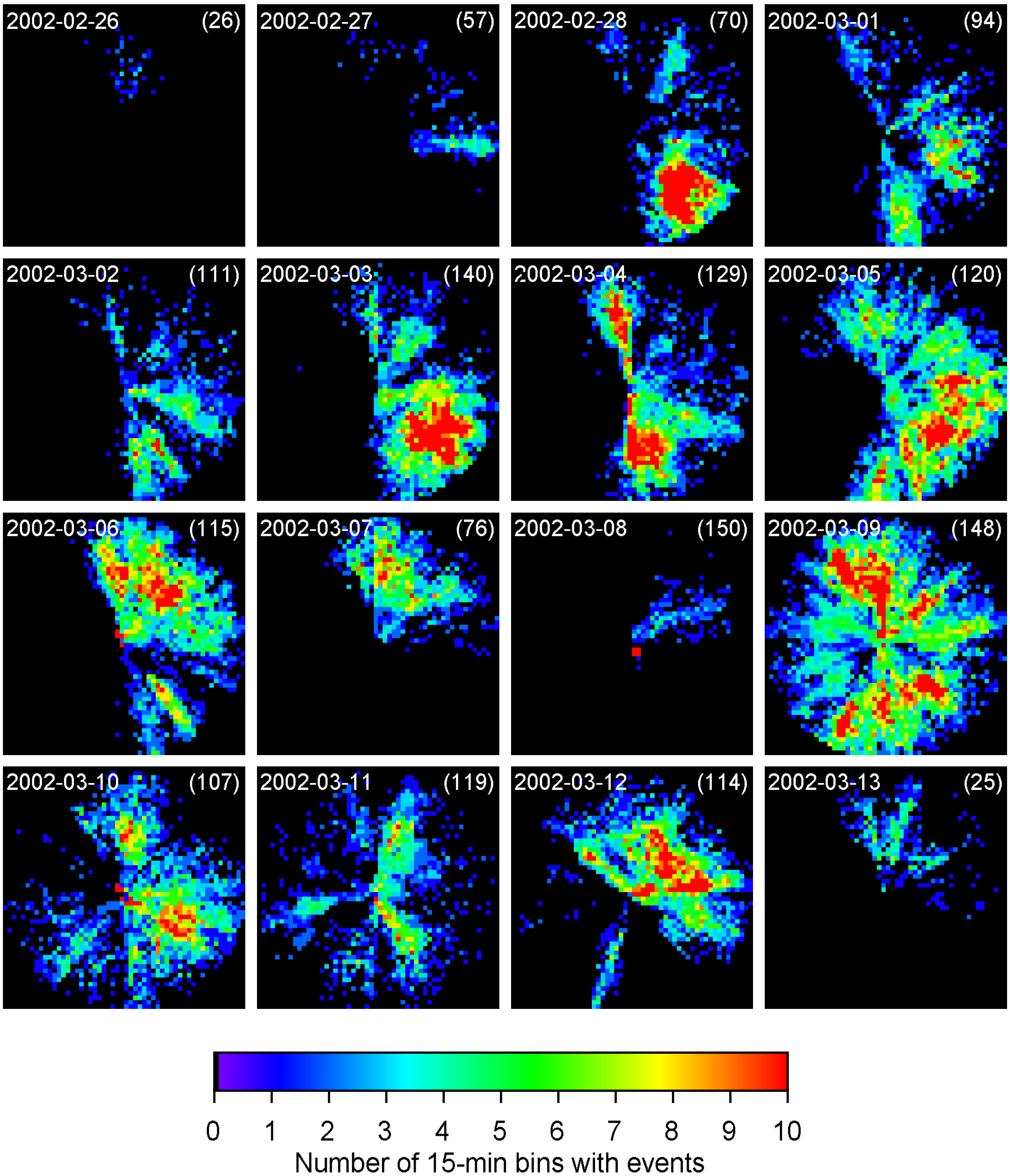



Figure 8: Same as Figure 7 but in 2002 February 26–March 13.

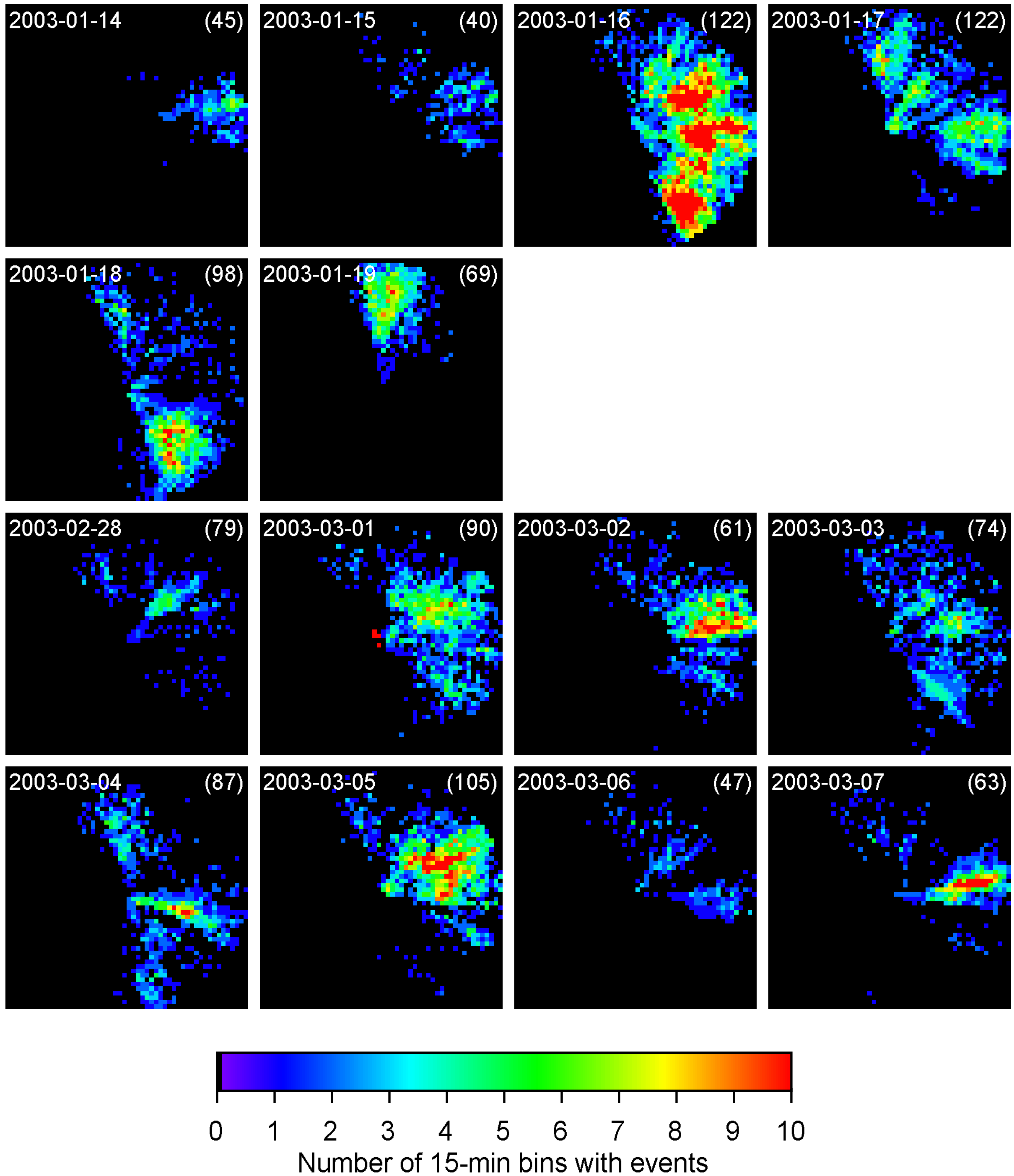



Figure 9: Same as Figure 7 but in 2003 January 14–19 and in 2003 February 28–March 7.

Table 1: Lightning Flashes Near Cerro Chascón Recorded by the LIS

| UTC | | Latitude | Longitude | Distance | Direction | Radiance |
|---|---|---|---|---|---|---|
| Date | Time | (deg) | (deg) | (km) | (deg) | ($\mu$J m$^{-2}$ sr$^{-1}$) |
| 1998-01-03 | 22:34:24.3282 | −23.083 | −67.085 | 62.2 | 96.9 | 2285275 |
| 1998-01-18 | 22:10:31.1798 | −22.873 | −67.821 | 20.3 | 316.3 | 92548 |
| 1998-01-21 | 20:08:57.1851 | −22.988 | −67.407 | 29.0 | 85.6 | 255724 |
| 1998-01-21 | 20:09:30.5666 | −23.045 | −67.346 | 35.3 | 95.8 | 168602 |
| 1998-01-21 | 20:09:36.6202 | −22.916 | −67.374 | 33.9 | 73.4 | 63003 |
| 1999-01-26 | 20:47:53.0218 | −22.765 | −67.126 | 63.7 | 66.5 | 1266056 |
| 1999-01-26 | 20:47:53.7078 | −22.773 | −67.103 | 65.5 | 68.0 | 735630 |
| 1999-01-31 | 17:58:25.0219 | −22.883 | −67.213 | 50.7 | 75.1 | 247942 |
| 1999-02-27 | 21:00:35.7960 | −23.016 | −67.247 | 45.2 | 90.8 | 70198 |
| 1999-03-02 | 19:00:10.9246 | −23.074 | −67.088 | 61.8 | 96.1 | 74387 |
| 1999-03-02 | 19:00:35.1178 | −23.047 | −67.066 | 63.8 | 93.4 | 22770 |
| 1999-03-10 | 22:13:55.0034 | −22.896 | −67.552 | 19.0 | 50.4 | 3317010 |
| 1999-03-10 | 22:13:55.2416 | −22.868 | −67.606 | 18.1 | 30.6 | 9576827 |
| 1999-03-12 | 21:25:53.9318 | −23.237 | −67.228 | 53.5 | 116.2 | 742483 |
| 1999-03-13 | 20:13:47.2285 | −23.241 | −67.718 | 26.0 | 186.9 | 328422 |
| 2000-01-17 | 20:43:00.7153 | −22.968 | −67.421 | 27.8 | 81.1 | 308106 |
| 2000-01-17 | 20:43:14.1925 | −22.958 | −67.313 | 38.9 | 82.1 | 21214 |
| 2000-01-17 | 20:43:14.6794 | −22.900 | −67.323 | 39.4 | 73.3 | 291356 |
| 2000-01-19 | 19:55:18.9683 | −23.042 | −67.735 | 5.8 | 234.6 | 88465 |
| 2000-01-21 | 19:05:23.2120 | −23.212 | −67.296 | 46.1 | 117.1 | 164353 |
| 2000-01-21 | 19:06:03.4944 | −23.179 | −67.324 | 41.9 | 114.8 | 253239 |
| 2000-01-21 | 19:06:14.5682 | −23.242 | −67.265 | 50.5 | 118.6 | 156913 |
| 2000-12-10 | 18:42:48.3062 | −23.069 | −67.158 | 54.7 | 96.3 | 2475955 |
| 2000-12-12 | 17:54:17.3912 | −22.904 | −67.407 | 31.2 | 69.5 | 89908 |
| 2001-01-19 | 22:07:17.5923 | −22.825 | −67.237 | 50.6 | 67.8 | 52358 |
| 2001-01-19 | 22:07:33.2394 | −22.796 | −67.160 | 59.1 | 68.0 | 101884 |
| 2001-01-24 | 19:16:51.4140 | −23.163 | −67.615 | 18.8 | 153.9 | 372449 |
| 2001-01-24 | 19:17:21.4905 | −23.147 | −67.617 | 17.1 | 151.9 | 440875 |
| 2001-01-24 | 19:17:55.7906 | −23.194 | −67.652 | 21.0 | 168.3 | 89138 |
| 2001-01-26 | 18:28:33.8227 | −22.835 | −67.490 | 28.3 | 48.8 | 169445 |
| 2001-01-28 | 17:40:05.2652 | −22.840 | −67.602 | 21.0 | 27.4 | 2519730 |

Note: Events recorded in the $0.5^\circ \times 1.0^\circ$ area (56 km × 102 km) centered at 23.0° S and 67.5° W in a period from 1997 December to 2003 December (see Figure 3). Distance and direction of flashes from the summit of Cerro Chascón (23.01° S, 67.69° W). North is 0° and east is 90°. Time sampling is incomplete.

Table 2: Lightning Flashes Near Cerro Chascón Recorded by the LIS (continued)

| UTC | | Latitude | Longitude | Distance | Direction | Radiance |
|---|---|---|---|---|---|---|
| Date | Time | (deg) | (deg) | (km) | (deg) | ($\mu$J m$^{-2}$ sr$^{-1}$) |
| 2001-02-06 | 19:41:38.3164 | −23.000 | −67.665 | 2.8 | 68.2 | 210058 |
| 2001-02-06 | 19:41:39.0772 | −22.907 | −67.679 | 11.6 | 6.1 | 284522 |
| 2001-02-06 | 19:41:50.5635 | −22.911 | −67.649 | 11.9 | 22.5 | 432624 |
| 2001-02-06 | 19:41:56.3629 | −23.193 | −67.516 | 27.1 | 136.4 | 53217 |
| 2001-02-06 | 19:41:56.4076 | −23.130 | −67.499 | 23.7 | 122.1 | 161060 |
| 2001-02-06 | 19:41:59.6337 | −22.925 | −67.621 | 11.8 | 39.1 | 51088 |
| 2001-02-06 | 19:42:08.6115 | −23.128 | −67.513 | 22.4 | 123.7 | 536233 |
| 2001-02-06 | 19:42:09.6426 | −23.086 | −67.604 | 12.2 | 131.5 | 186776 |
| 2001-02-06 | 19:42:19.8591 | −22.899 | −67.662 | 12.8 | 14.2 | 279466 |
| 2001-02-06 | 19:42:30.2780 | −22.933 | −67.541 | 17.5 | 62.7 | 63989 |
| 2001-02-06 | 19:42:30.7217 | −22.940 | −67.604 | 11.8 | 50.9 | 132733 |
| 2001-02-06 | 19:42:37.8694 | −23.051 | −67.514 | 18.5 | 103.1 | 282482 |
| 2001-03-10 | 19:52:19.0645 | −23.247 | −67.635 | 27.1 | 166.9 | 506479 |
| 2001-03-10 | 19:52:26.0348 | −23.182 | −67.631 | 20.2 | 161.1 | 107967 |
| 2001-12-19 | 18:16:36.7949 | −23.098 | −67.127 | 58.3 | 98.9 | 105051 |
| 2001-12-19 | 18:16:39.4969 | −23.171 | −67.157 | 57.3 | 106.8 | 247388 |
| 2001-12-19 | 18:17:02.9463 | −23.084 | −67.011 | 69.8 | 96.2 | 87224 |
| 2001-12-19 | 18:17:09.0035 | −22.863 | −67.257 | 47.1 | 71.2 | 584715 |
| 2001-12-19 | 18:17:25.0893 | −23.099 | −67.084 | 62.6 | 98.4 | 586638 |
| 2001-12-19 | 18:17:44.6699 | −23.027 | −67.050 | 65.3 | 91.5 | 100989 |
| 2002-02-01 | 20:10:53.0770 | −22.827 | −67.135 | 60.2 | 71.8 | 950507 |
| 2002-02-01 | 20:11:06.0201 | −22.810 | −67.263 | 49.0 | 64.9 | 1165950 |
| 2002-02-01 | 20:11:25.1982 | −22.823 | −67.099 | 63.8 | 72.4 | 82024 |
| 2002-02-01 | 20:11:37.7906 | −22.819 | −67.076 | 66.2 | 72.7 | 459716 |
| 2002-02-01 | 20:11:49.0904 | −22.817 | −67.148 | 59.4 | 70.4 | 174371 |
| 2002-02-16 | 19:20:32.0557 | −22.933 | −67.407 | 30.1 | 74.8 | 357119 |
| 2002-02-16 | 19:21:09.4768 | −23.076 | −67.114 | 59.2 | 96.5 | 539124 |
| 2002-07-03 | 21:56:15.0036 | −23.065 | −67.874 | 19.8 | 253.4 | 7864770 |
| 2002-07-03 | 21:56:19.6945 | −23.180 | −67.768 | 20.6 | 204.6 | 990129 |
| 2002-07-03 | 21:57:27.4392 | −23.059 | −67.725 | 6.5 | 215.5 | 2886323 |
| 2003-01-16 | 18:06:56.5438 | −23.200 | −67.079 | 65.9 | 107.3 | 366234 |
| 2003-01-16 | 18:07:22.4248 | −23.181 | −67.068 | 66.3 | 105.4 | 84230 |
| 2003-01-16 | 18:07:22.9605 | −23.185 | −67.071 | 66.1 | 105.8 | 380829 |
| 2003-01-16 | 18:07:45.8517 | −23.153 | −67.057 | 66.5 | 102.7 | 967051 |

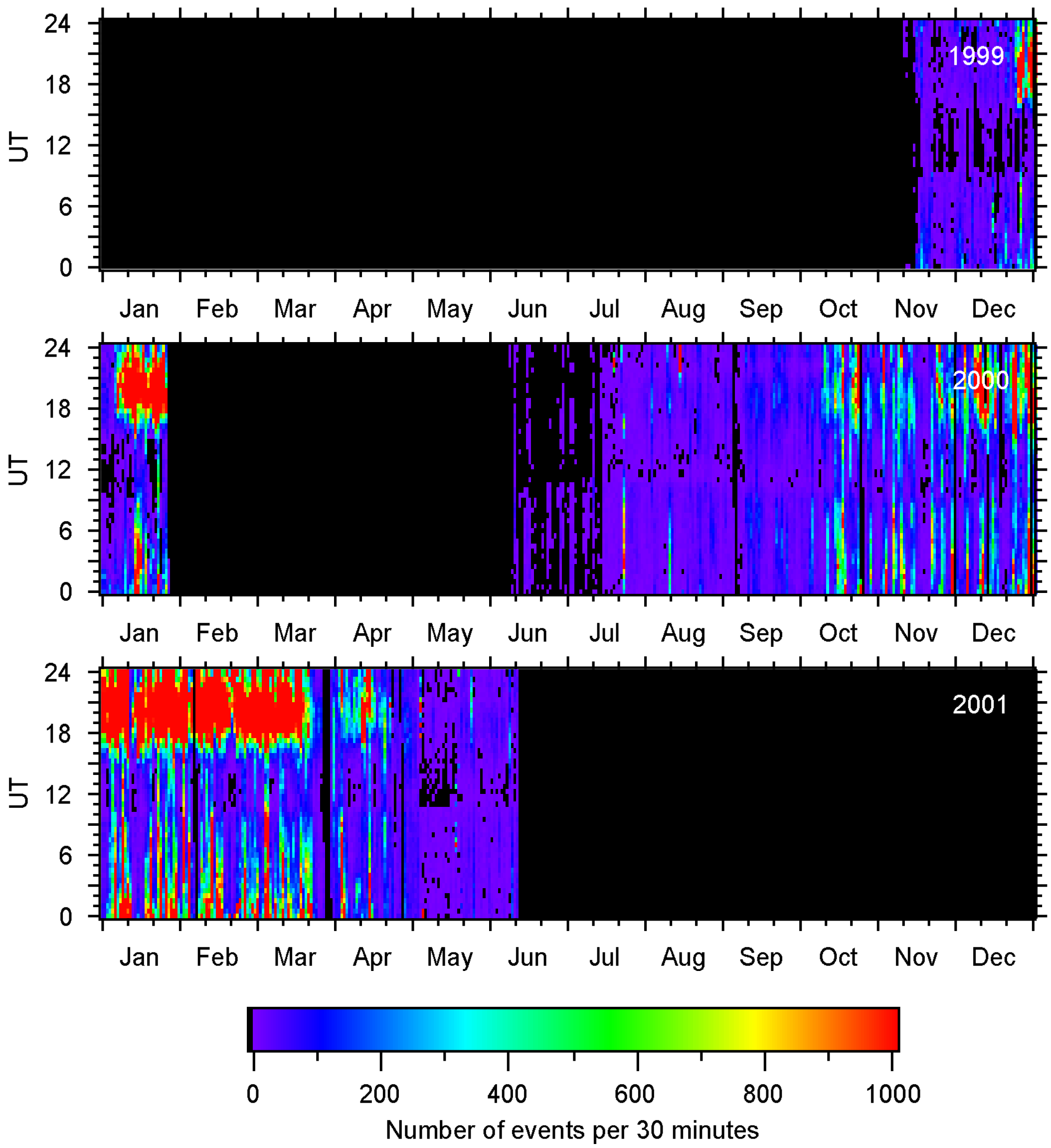



Figure 10: Lightning strike rate measured with the Boltek StormTracker. The instrument ran from 1999 November 9 to 2000 January 27 and from 2000 June 8 to 2001 June 12. Local solar time is UT − 4h31m.

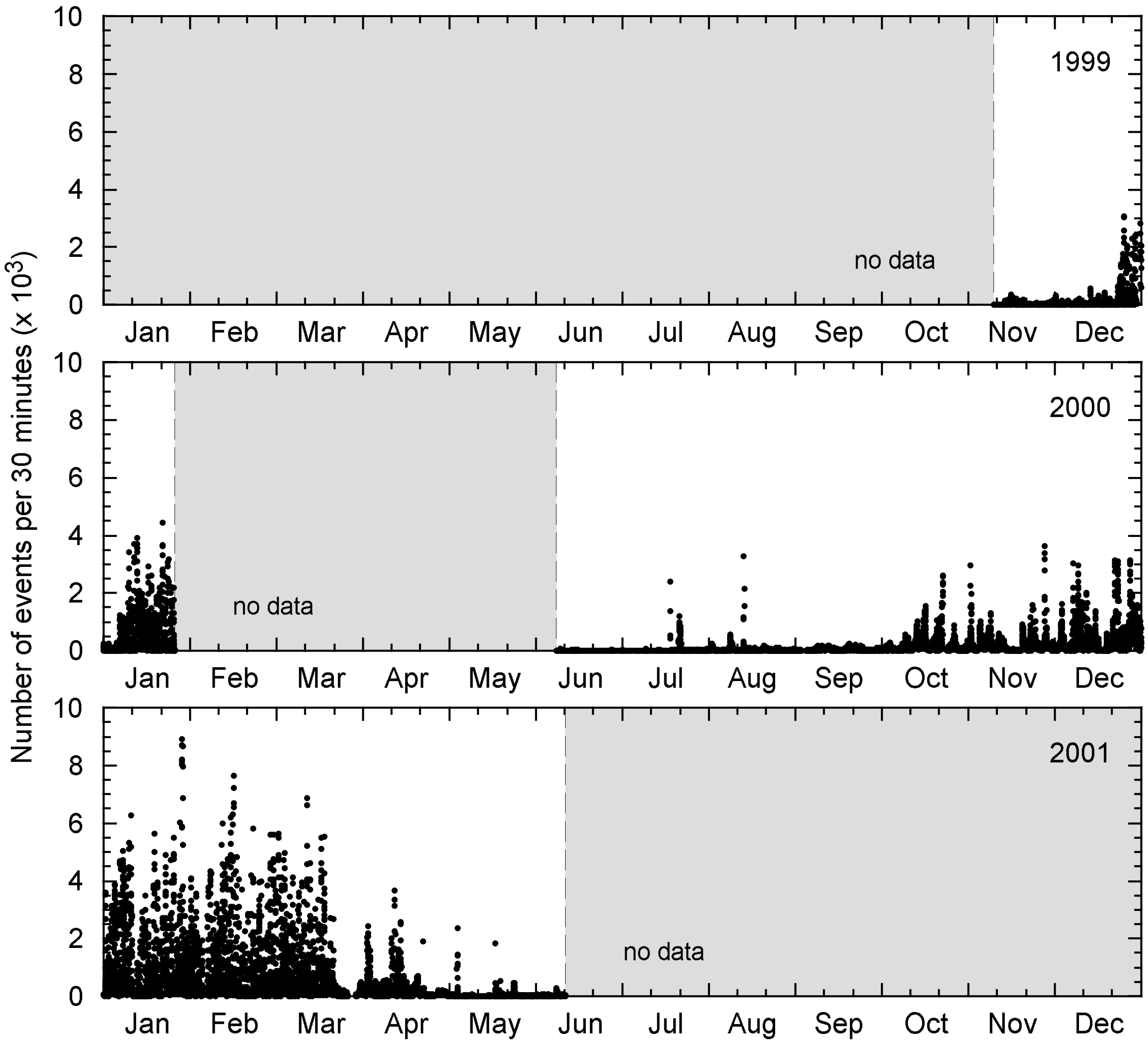



Figure 11: Seasonal variation of lightning strike rate measured with the Boltek StormTracker. The strike rate units are counts per 30 minutes. The instrument was not operating from 2000 January 27 to June 8.

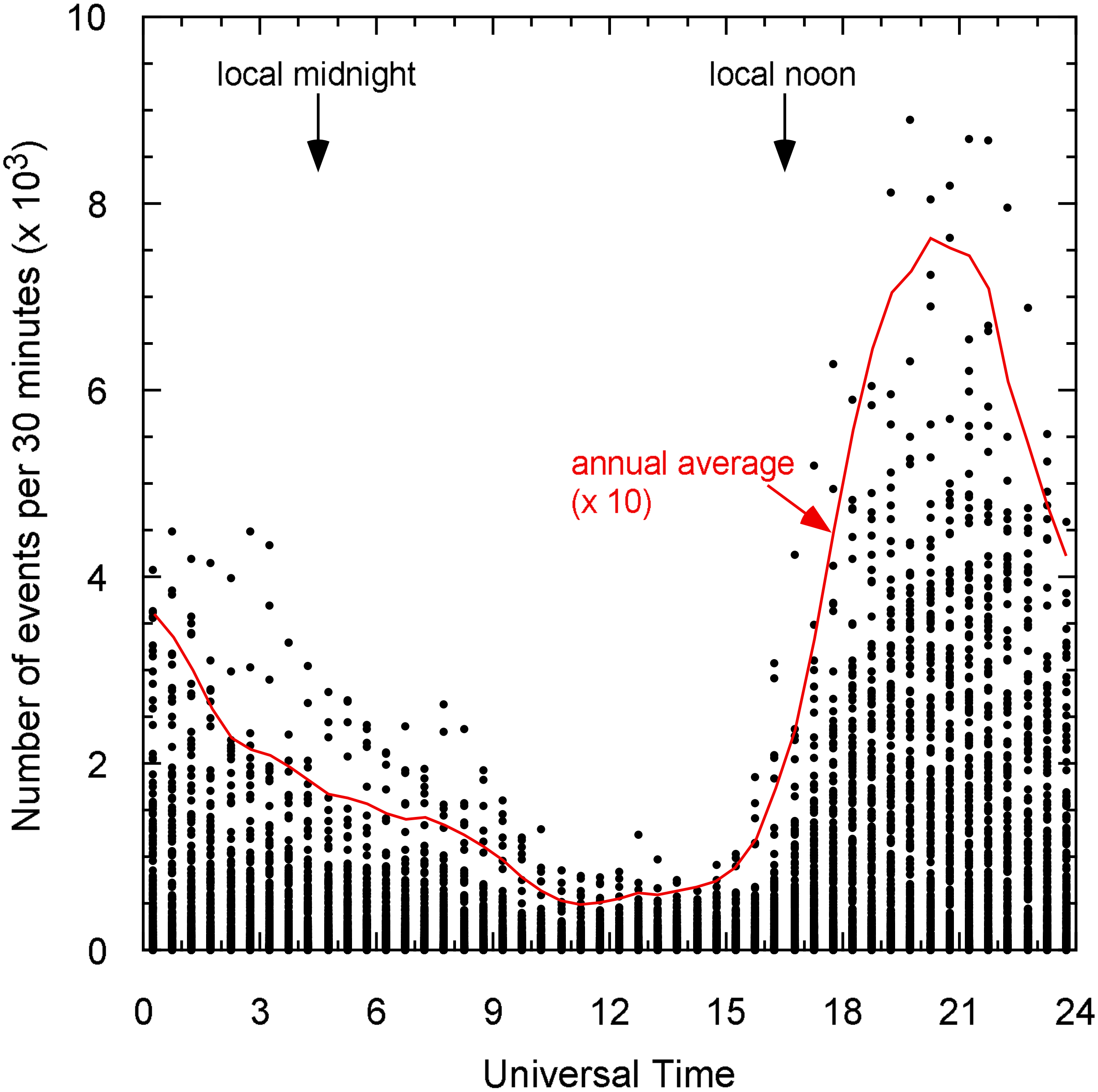



Figure 12: Diurnal variation of the lightning strike rate measured with the Boltek StormTracker. The strike rate units are counts per 30 minutes. Annual mean value from 2000 June 10 to 2001 June 9, multiplied by 10, is shown as a red line. Local solar time is UT − 4h31m.

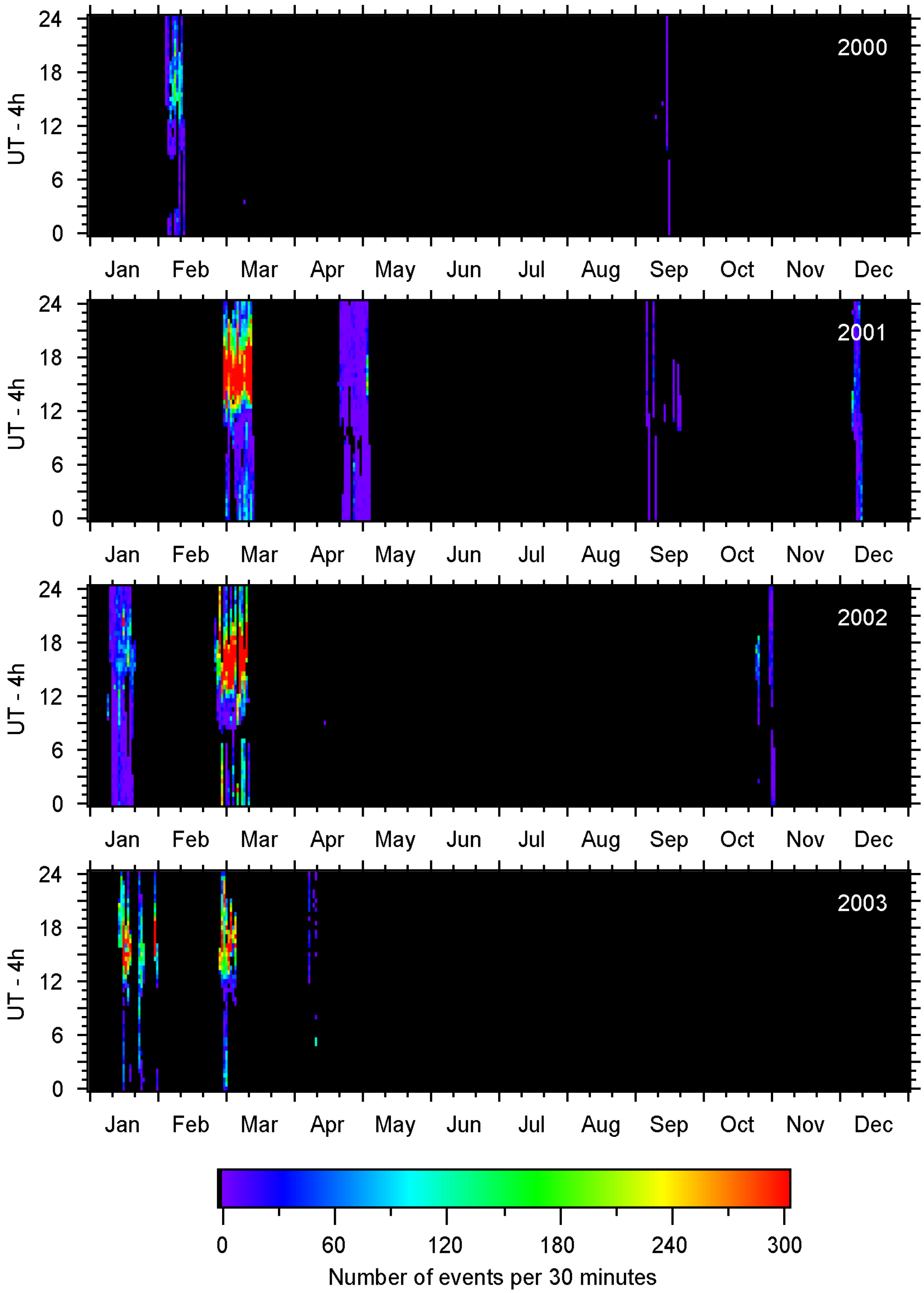



Figure 13: Nearby lightning strike rate measured with the Technocrat 22-DV storm detector, binned every 30 min. The instrument was operating only when the periods not coded in black.

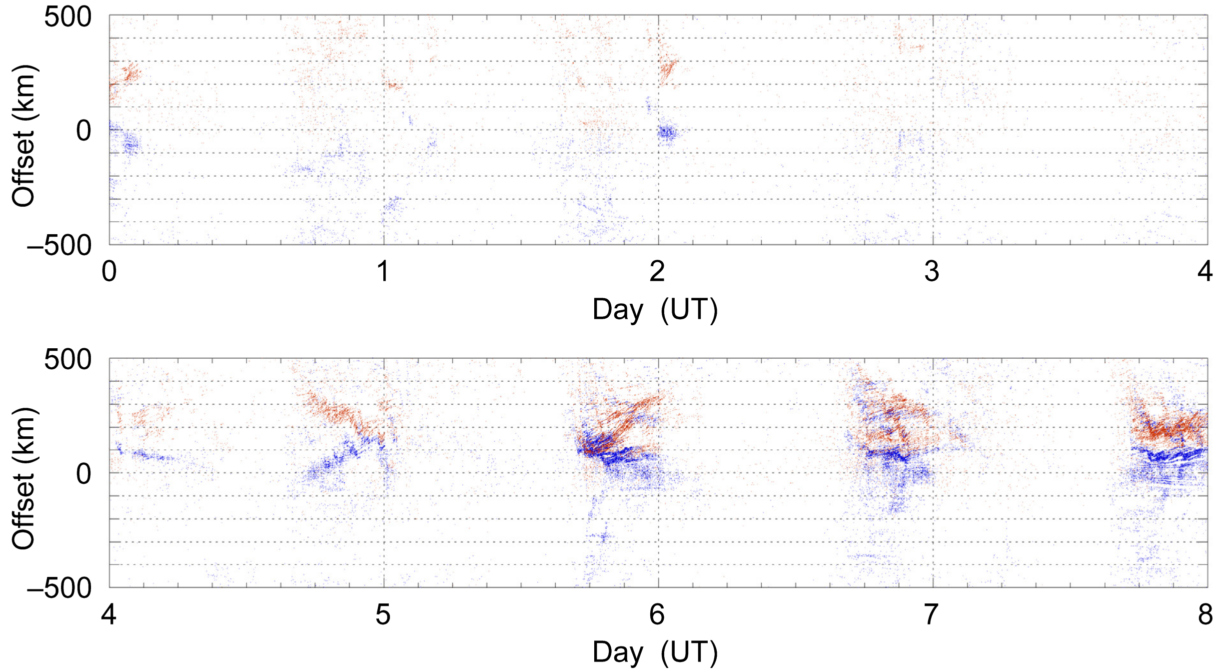
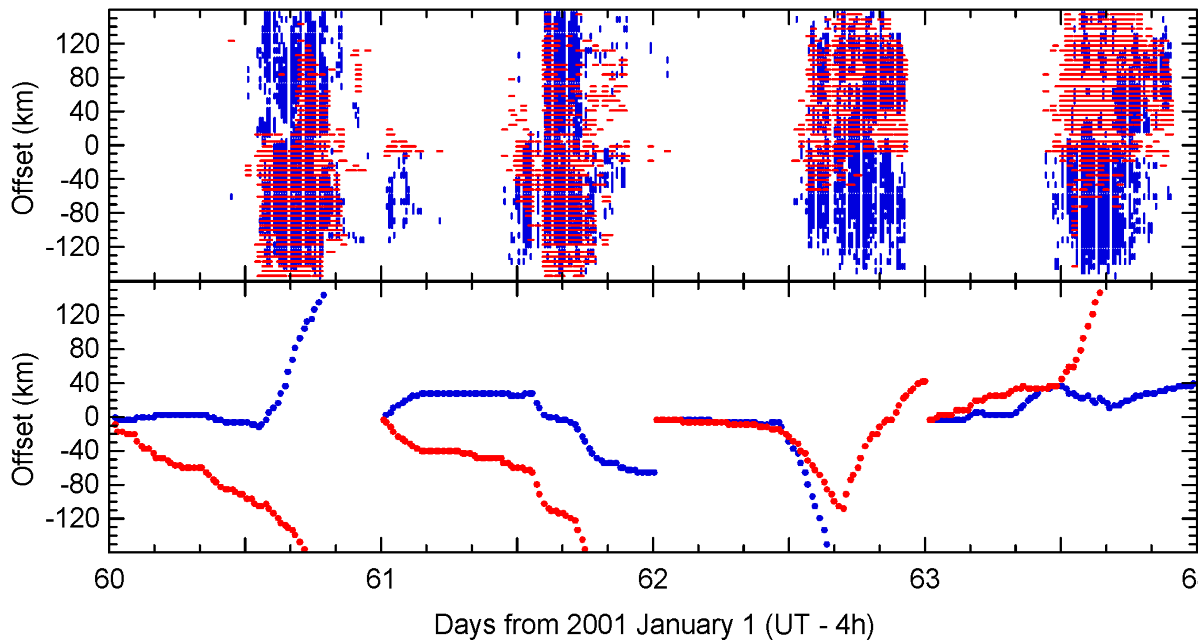



Figure 14: Storm cloud motion recorded by the Boltek StormTracker in the first eight days of 2000 January. In this diagram, day 0.0 represents 0:00 UT on January 1. Red and blue dots show, respectively, east–west and north–south offsets from the NRAO container at Llano de Chajnantor. Positive offsets are east and north. Storm clouds frozen in a wind from the west would appear in this diagram as features with positive east–west slopes, but without significant north–south slopes.



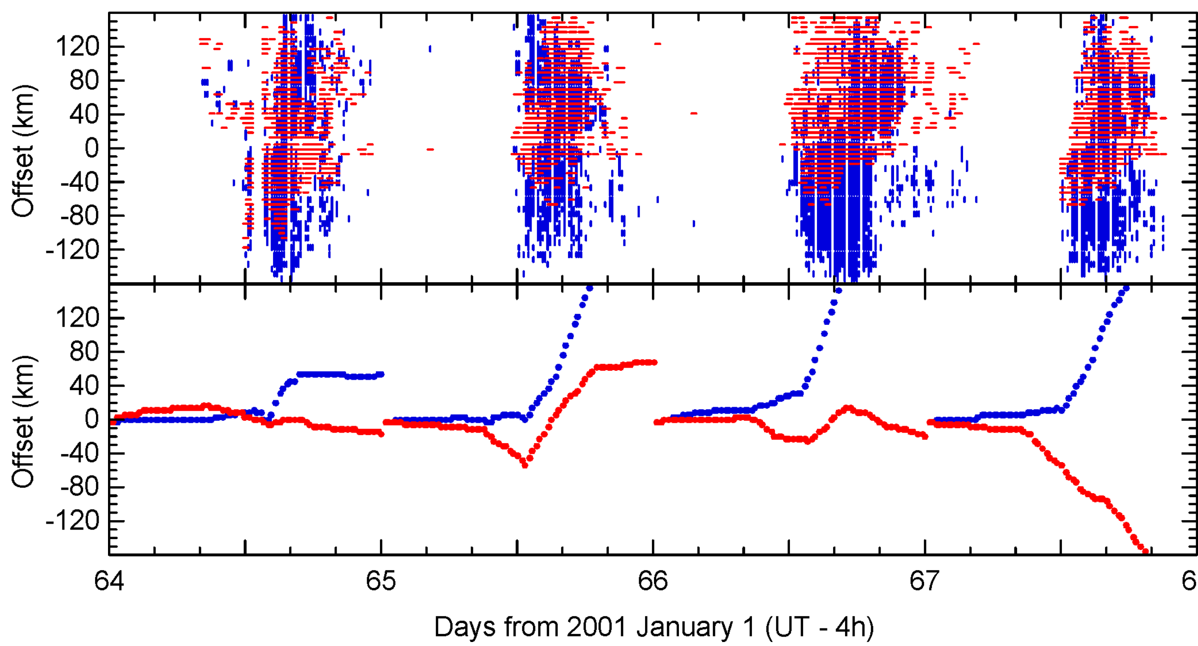




Figure 15: Nearby storm cloud motion recorded by the Technocrat storm sensor in stormy days from 2001 March 2 through March 9. Red and blue bars show, respectively, east–west and north–south offsets from the NAOJ container at Pampa La Bola. Positive offsets are east and north. At the bottom of each figure, motion expected from surface wind measured with a nearby weather station [9] is shown. Red and blue dots show east–west and north–south offsets, respectively.