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Lightning associated with the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska

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Abstract

Lightning occurred associated with the ash clouds of all three eruptions of Mt. Spurr Volcano in 1992. Lightning was detected on seismograms as simultaneous spikes and simultaneous gain-ranging (a feature that normally lowers the gain at a station when the signal level begins to saturate). Spikes had typical durations of 0.04–0.05 s. Using uniform criteria we found 28 lightning flashes in the June 27th eruption, 29 in the August 18th eruption, and three in the September 17th eruption. We measured peak voltages on station RSO, 94 km SSW, to determine the relative strengths of lightning, and found that the August lightning was strongest, June weakest, and September intermediate. Based on relative signal strengths at different stations, we found evidence for different lightning geometries between the June and August eruptions, during which prevailing winds blew the ash clouds to the north and east, respectively. For all three eruptions the first lightning was recorded 21–26 min after the onset of the eruption, suggesting that charge separation occurred in the convecting cloud rather than at the vent. Data recorded by a Bureau of Land Management lightning detection system for the August eruption showed negative polarities for the first 12 recorded flashes and a positive polarity for the last. This suggests a charge separation based on particle size, in which negative charge is found for larger particles which fall first, and positive charge remains on smaller particles which remain suspended longer. All three eruptions had similar durations of 3.5–4 h, and tephra volumes of 44–56 million cubic meters. The August eruption, however, produced stronger volcanic tremor, 30 cm^2 reduced displacement as compared with 16 cm^2 for June, and greater gas, 400 ± 120 kt SO_2 for August and 200 ± 60 kt for June. Thus lightning strength correlates with both tremor amplitude and magmatic gas content. The August eruption occurred during the lightest winds, so the ash cloud and charge separation were vertically oriented and favored cloud-to-ground lightning. The September eruption occurred during the coldest and driest atmospheric conditions, which may explain the small amount of lightning. In general, volcanic lightning is important because it can help confirm that explosive eruptions are in progress, although the value of the information may be limited by the long delay from eruption onset to first lightning and the variability of eruptive and atmospheric conditions.

Keywords: Mt. Spurr Volcano; ash clouds; volcanic lightning

1. Introduction

Volcanic lightning is a common yet poorly studied phenomenon. Lightning has occurred at more than 55 volcanoes in association with eruptions of various types and sizes; it is especially common during larger eruptions (Table 1). Reports at night are slightly more numerous than those during the day, presumably because lightning is easier to see at night. Volcanic lightning was responsible for the only death reported

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Table 1
Lightning at selected volcanoes from literature search

Volcano	Dates	Comment	References
Akutan	10 April 1992	–	J. Paskievitch, pers. commun. (1992)
Aniakchak	1 May 1931	–	Volcano Quarterly (1993)
Arenal	29 July 1968	–	W. Melson, pers. commun. (1994)
Asama	1783	–	Krafft (1993)
Aso	13 June–6 September 1979	Seven occasions	McClelland et al. (1989)
Augustine	23 January 1976	–	Kienle and Swanson (1985)
Bezimianny[a]	31 March 1956	–	Gorshkov (1959)
Bulusan	15 April 1981	–	McClelland et al. (1989)
Cerro Negro	1971	–	Viramonte et al. (1971), Fisher et al. (1997) (photo by J. Viramonte)
Chikurachki	19–20 November 1986	Two occasions	SEAN (1986), BVE (1989)
El Chichon	4 April 1982	–	Havskov et al. (1983)
Etna	1819, 3–4 August 1979, 16–17 April 1980	–	McClelland et al. (1989), Krafft (1993)
Fernandina	11 June 1968, 8 August 1978	Two occasions	Simkin and Howard (1970), McClelland et al. (1989)
Fuego	16 September 1978, 22 March 1979	Two occasions	McClelland et al. (1989)
Galeras	7 June 1993	–	GVN (1993)
Galunggung	Early August–3 December 1982	Six occasions	Katili and Sudradjat (1984), McClelland et al. (1989), Gourgaud et al. (1989), Krafft (1993)
Gorely[a]	1980–1981 or 1984–1986	–	Fedotov and Masurenkov (1991)
Grimsvotn caldera	Summer–fall 1996	–	Benediktsson (1996) (video)
Heimaey	1973	–	Brook et al. (1973)
Hibok–Hibok	1951	–	Alcaraz (1989)
Hudson	8–12 August 1991	Two occasions	GVN (1991)
Karymsky	3–6 December 1976, 13 October 1996	–	Rulenko (1981), AVO Bimonthly (1996)
Katla	1755	–	Anon. (1863), in Pounder (1980)
Kilauea	1924	–	Natl. Park Service display
Komagatake	17 June 1929	–	Poster Display (1995), video
Krakatau	1883, 10 July 1978, 2–5 October 1978, 14 September 1979, 20 October 1981, 17 May 1997	Six occasions	Judd (1888), Lane (1966), Francis (1976), Simkin and Fiske (1983), McClelland et al. (1989), M. Lyvers, pers. commun. (1997)
Langila	12 November, 26 December 1982	Two occasions	McClelland et al. (1989)
Manam	27 March 1982, 30 June 1987	–	McClelland et al. (1989), BVE (1990)
Mayon	24 September 1984	–	McClelland et al. (1989)
Montserrat	1995?	–	“World’s Deadliest Volcanoes” (video)
Mount St. Helens	18 May 1980, late July 1983	Two occasions	Cobb (1980), McClelland et al. (1989)
Ngauruhoe	29 March 1974	–	Nairn et al. (1976)
Pacaya	1973	–	W.C. Buell photo
Paricutin	1943–1952	–	Green (1944), Gukiessez (1972), Luhr and Simkin (1993)

Table 1 (*continued*)

Volcano	Dates	Comment	References
Pavlof	4 November 1996	–	J. Painter, pers. commun. (1997)
Pelee	9 July 1902	–	Anderson and Flett (1903)
Rabaul, both Vulcan and Tavurvur	19 September 1994	–	GVN (1994)
Redoubt	15 February–15 April 1990	11 occasions	Hoblitt (1994)
Ruapehu	1945, 11 October 1995	Two occasions	Blong (1984), GVN (1995), Schneider (1995)
Ruiz	11 September 1985	–	McClelland et al. (1989)
Sakurajima	1914, 6 December 1976, 24 November–26 December 1979, 17 February 1988, 18 May 1991	13 occasions	Abe (1979), McClelland et al. (1989), Newcott and Menzel (1993), Ryan (1994) (photo by T. Takayama), Fisher et al. (1997)
Santa Maria	24–26 October 1902	–	Sapper (1905)
Shiveluch[a]	1964	–	Gorshkov and Dubik (1970)
Soputan	26 August, 9 November 1982	Two occasions	McClelland et al. (1989)
Soufriere, St. Vincent	1979	–	Sheppard et al. (1979)
Spurr	9 July 1953, 27 June 1992, 18 August 1992, 17 September 1992	Four occasions	Juhle and Coulter (1955), Wilcox (1959), Davis and McNutt (1993), Paskievitch et al. (1995)
Stromboli(?)	?	Questionable	Krafft (1993), cover
Surtsey	November 1963, February 1964	Two occasions	Anderson et al. (1965)
Taal	1911, 1965[a], 6 September 1976, 10 October 1976	Four occasions	Pratt (1911), Carroll and Parco (1966), McClelland et al. (1989)
Tarawera	1886	–	Pond and Smith (1886)
Thera	1470 BC	–	Pounder (1980)
Tokachi	1926, 29 June 1962, 24 December 1988	Three occasions	H. Okada, pers. commun. (1995), Katsui et al. (1990)
Tolbachik (new)	1976?	–	Fedotov and Masurenkov (1991)
Ulawun	6–7 October 1980	–	McClelland et al. (1989)
Unknown	–	–	Saavedra and Ramis (1991, p. 99)
Usu	7 August 1977, 24 August 1978, 13 September 1978	–	Niida et al. (1980), McClelland et al. (1989)
Vesuvius	79 AD, 1660, 1707, 1767, 1779, October 1822, 1906, March 1944	Eight occasions	Jaggar (1906), Francis (1976), Krafft (1993), S. Martino Museum (painting), Goldsmith (1852), Lane (1966), Shore (1975)
Vulcan	29–30 May 1937	–	Johnson and Threlfall (1985), McKee et al. (1985)
Westdahl	6 February 1978	–	McClelland et al. (1989)

[a] Probable lightning (strong atmospheric electricity).

at Particutin (Luhr and Simkin, 1993) and also killed one person during the recent eruptions at Rabaul (GVN, 1994). Blong (1984) cites lightning observations and hazardous effects from five additional eruptions.

A further motivation to study lightning, in addition to the direct hazard, is the fact that its occurrence may be used to help confirm that an explosive eruption is in progress, when combined with seismic and acoustic data. This is especially true in areas in which lightning is not common, such as Cook Inlet and the Aleutians in Alaska, where the combination of volcanic tremor, acoustic blasts, and lightning would be compelling evidence that an eruption producing ash clouds was occurring. Such information would be useful for warning aircraft in areas too remote for conventional monitoring.

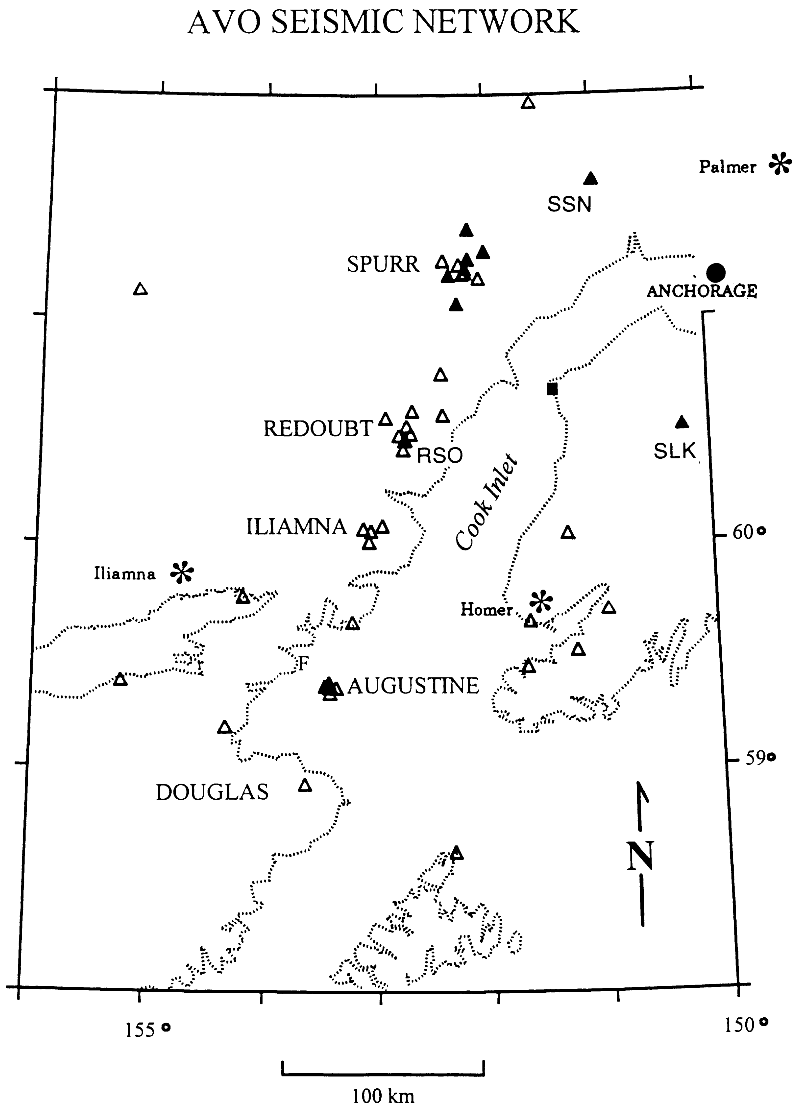


Fig. 1. Map showing local and regional seismic stations (triangles) and AVO lightning detection system stations (stars). Seismic stations that recorded lightning are shown as solid symbols. Selected regional stations are labeled. The central lightning processor is in Anchorage.

Lightning is a transient electric discharge with a typical path length of hundreds of meters to kilometers (Uman, 1987). A typical lightning flash or strike (if it hits something) consists of several component strokes occurring a few hundredths of a second apart. Flashes may be within a cloud (intracloud or IC lightning) or from a cloud to the earth (cloud-to-ground or CG lightning); other types such as cloud-to-cloud or cloud-to-air are less common. CG lightning is termed negative if it lowers negative charge to the ground, and positive if it lowers positive charge. Lightning produces several observable effects, including light, heat, thunder, and wide-band (<1 Hz to >1 GHz) radio waves. CG lightning produces radio waves with higher amplitudes and lower frequencies than IC lightning (Uman, 1987). However, IC lightning is the most common type and accounts for well over half of lightning that occurs in thunderstorms.

A lightning detection system, consisting of three sensors and a central processor, was installed in the Cook Inlet region by the Alaska Volcano Observatory (AVO) in 1991 (Hoblitt, 1994; Paskievitch et al., 1995). Lightning detection system station locations are shown in Fig. 1. This system recorded 171 lightning strokes during the August 1992 eruption of Mt. Spurr (Paskievitch et al., 1995) but none during the June or September eruptions. This was paradoxical because all three of the eruptions were quite similar in durations, tephra volumes, and plume heights, hence charge generation. A lightning detection system operated in central Alaska by the Bureau of Land Management (BLM) also recorded lightning during the August eruption, but was not operating during the June or September eruptions. Spurr's only other known historic eruption on June 9, 1953 was an especially rich source of lightning (Table 1; Juhle and Coulter, 1955). Juhle and Coulter quote from an Air Force press release of July 10, 1953:

> … Both planes … circled the volcano at about 05 h 25 m. They noticed the continuing increase in the intensity and size of the column of smoke (sic) with lightning flashes through its core every 30 seconds. … About 05 h 40 m Lieutenant Metzner climbed in order to estimate the height of the mushroom. The top of the stalk, or the bottom of the mushroom, was 30,000 feet and the top of the mushroom had climbed to 70,000 feet. Lightning was now flashing from top to bottom of the mushroom at three-second intervals.

We discovered that volcanic lightning at Spurr in 1992 was accidentally but fortuitously being recorded on seismic instrumentation. The seismic data showed that lightning occurred during all three eruptions in summer 1992. Understanding these data, solving the paradox with respect to the lightning detection system, and understanding the general relation of lightning to Spurr's eruptions are the main purposes of this paper. The paper takes a phenomenological approach to lightning because the data were accidental; we can comment on some features of the lightning but no experiment was designed specifically for lightning research. Nevertheless, some illuminating results have been obtained.

2. Mt. Spurr data

Evidence for lightning in Spurr's eruption columns comes from five distinct sources: (1) visual observations by people on the ground; (2) visual images on a slow-scan TV camera; (3) the AVO lightning detection system; (4) the BLM lightning detection system; and (5) seismic data. Each is briefly described below.

2.1. Visual observations

For the 1953 eruptions, the sole evidence for lightning comes from visual observations from pilots (Juhle and Coulter, 1955). In 1992 visual reports were obtained for the August 18 and September 16–17 eruptions, but not for June 27. Airborne observers saw lightning at 5:45 p.m. ADT (during daylight hours and 1 h after eruption onset) on August 18, 1992 (G. McGimsey, pers. commun., 1992). Observers on the ground about 18 km south southeast of Mt. Spurr saw lightning during the September 16–17 eruption, which occurred at night. (The June eruption occurred during daylight hours.) An account by M. Wyatt of the observations for the September eruption is as follows:

> At 0015 to 0030 (Sept. 17), it started up intensely. The ash got real thick, covering the ridge to the north from view. Lightning bolts were going one after another into the cone (of Crater Peak). … The ash cloud drifted east. There was much lightning all through the cloud, all the way from the cone to Cook Inlet (about 80 km).

(R. Waitt and T. Miller, pers. commun., 1992).

It is ironic that visual observations of lightning were made only for the September eruption, because, as we shall see, this eruption produced the lowest number of recorded lightning flashes.

2.2. Slow-scan TV camera

In 1992 AVO operated a slow-scan TV system at Kasilof, 125 km SSE of Mt. Spurr across Cook Inlet. Every 30 s the camera obtained an image which was telemetered to Fairbanks and recorded on a video cassette recorder. During the September eruption, the camera recorded a strong glow directly above the crater (Fig. 2b and c) which we interpret to be incandescence from the erupting tephra. Other images

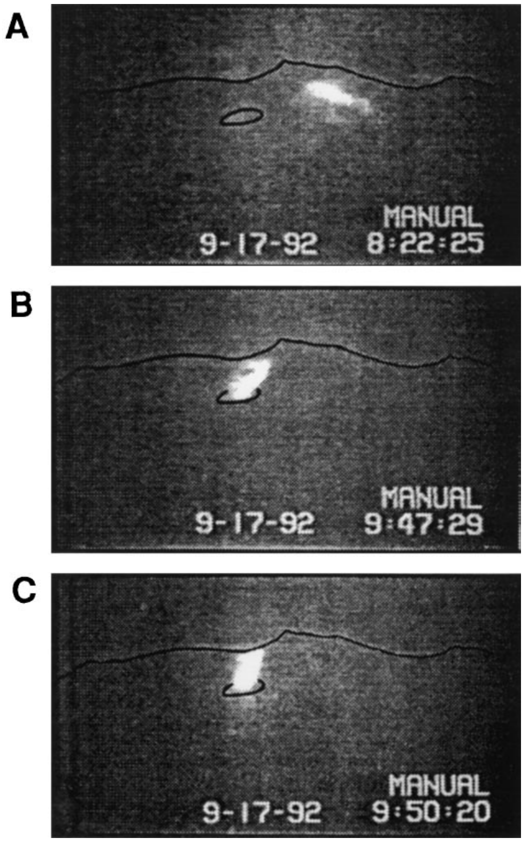


Fig. 2. Slow-scan TV images of the September 16–17, 1992 eruption from Kasilof, 120 km south-southeast of Mt. Spurr. Summit and crater are drawn in for reference: (A) lightning illuminates volcanic plume east of Crater Peak vent early in the main phase of the eruption; (B) and (C) strong incandescence at Crater Peak midway through the main phase of the eruption. Times are UTC.

show a strong glow east of the crater, downwind, which we interpret to be lightning (Fig. 2a). Remembering that lightning is a transient signal, and that the camera records only a single image every 30 s, the recording of a lightning flash was fortuitous.

2.3. AVO lightning detection system

A commercial lightning detection system (sensors are LPATS Remote Receivers, Series III, 86-008-A and antennas are 8 ft flexible CB whip antennas by Shakespeare; system manufactured by Atmospheric Research Systems, Inc.) was installed by AVO in 1991 to help monitor possible eruptions of Cook Inlet volcanoes (Hoblitt, 1994; Paskievitch et al., 1995). The system consists of three sensors which telemeter their data to a central processing site in Anchorage (Fig. 1). The lightning detection system can determine locations and polarities (positive or negative) of strokes, and contains algorithms to determine stroke type (CG or IC) based on time between peak stroke signal and first polarity change (Paskievitch et al., 1995). The lightning detection system recorded lightning only during the August 18 Spurr eruption, during which 171 strokes occurred in a 10 km circular zone centered 5 km east (downwind) of Crater Peak. Of the 171 strokes, 70% were IC and 30% were CG using the algorithm described above. All the detected strokes were of positive polarity and occurred after 6:30 p.m. ADT (1 h 48 min after eruption onset).

2.4. Bureau of Land Management

The Bureau of Land Management (BLM) operated a network of seven lightning detectors (sensors are model 141 ALDF and analyzer is model 281 APA, manufactured by Lightning Location and Protection, Inc.) in central Alaska and one in Canada during the summer of 1992 as part of its program to detect lightning strikes they may cause forest fires (Fig. 3). This system recorded 13 strikes during the August 18 eruption, but was not operated during the June or September eruptions. The 13 strikes in August coincided within 0.01 s with lightning deduced on seismograms (see below), and occurred between 5:43 p.m. ADT and 7:51 p.m. ADT, or 1–3 h after the eruption onset and including the time of visual observations. Although few in number, the BLM data were important because they contained information about the relative amplitude and polarity of the lightning strikes. (Information on absolute amplitudes was not recorded in 1992, and only arbitrary relative amplitudes were recorded, a situation that was later rectified; T. Weatherby, pers. commun., 1999.) The BLM system is designed primarily to detect vertically oriented CG lightning strikes.

2.5. Seismic systems

AVO operates nine telemetered short-period vertical seismometers within 20 km of Mt. Spurr (Fig. 4). Each field seismic station consists of a seismometer, a pre-amplifier, a voltage controlled oscillator (VCO), a

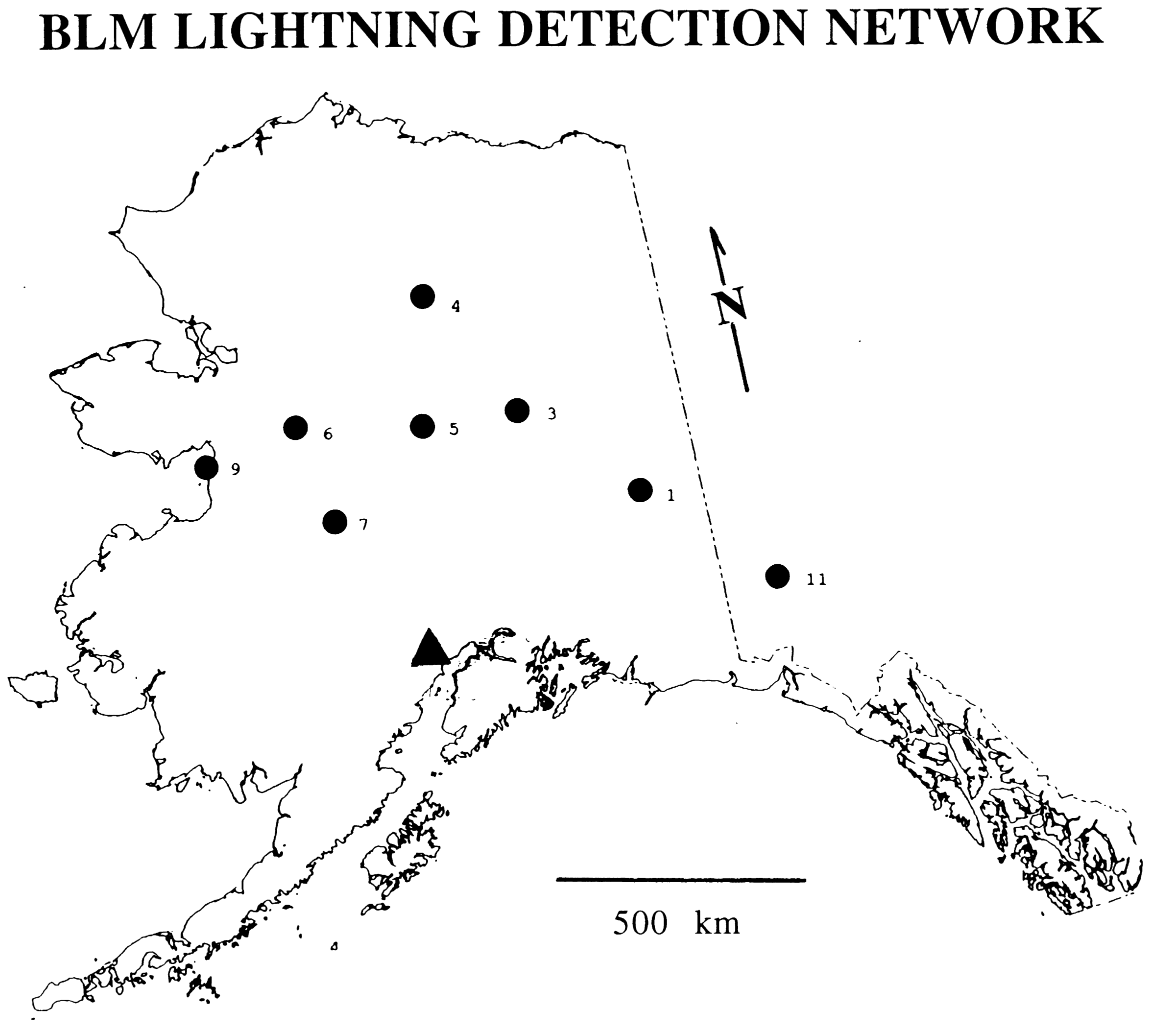


Fig. 3. Map showing BLM lightning detection stations (numbered dots) and Mt. Spurr (triangle). The BLM stations are more than 300 km from the volcano, whereas all the seismic stations that recorded lightning are on Cook Inlet within 100 km.

transmitter, antenna, batteries, and various cables. The stations are designed to operate independently and telemeter their data by FM radio to a common collection point, after which the data are transmitted via telephone lines. Stations are serviced approximately once per year and have sufficient battery power to operate for the entire year, 24 h per day. Data are recorded continuously in Fairbanks in digital form at a sample rate of 120 Hz (Sonafrank et al., 1991). The central recording system uses GPS and GOES clocks to record absolute time.

Some of the VCOs are a special model designated the A1VCO, which incorporates a feature known as automatic gain control or sometimes as 'gain ranging' (Rogers et al., 1980). This feature automatically lowers the gain or magnification of the seismic signal in order to keep large signals on scale. It adds a known identification pulse to the signal, systematically delayed, so that analysts will know where the gain ranging occurred. Gain ranging at Spurr seismic stations covers two ranges; a factor of 10 reduction in magnification followed 3 s later by a single reference spike, and a further factor of 50 reduction (total reduction 500 ×) followed 45 s later by an eight-cycle

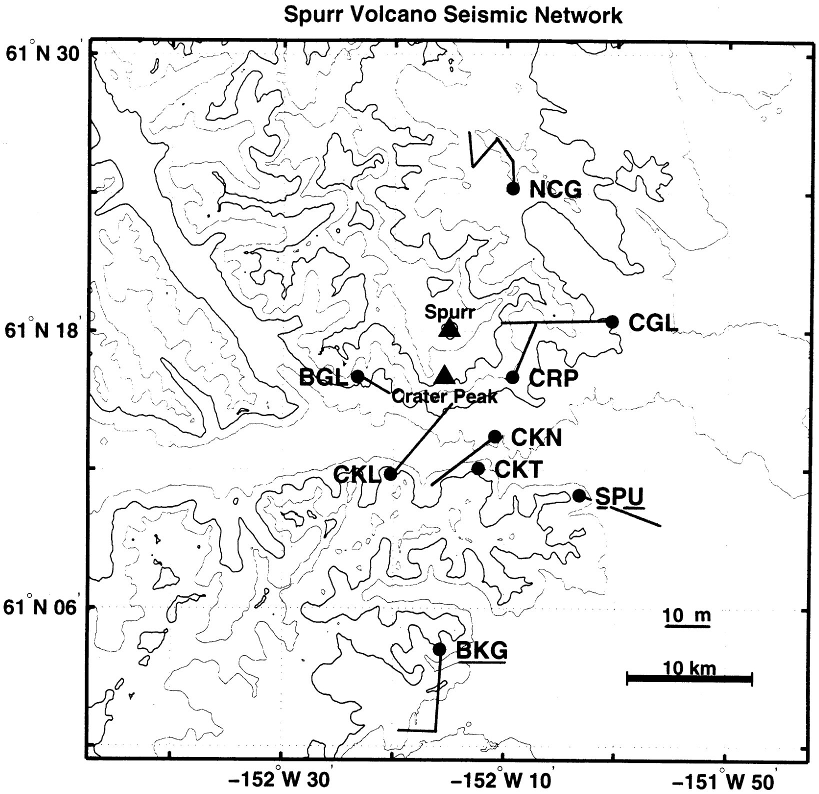


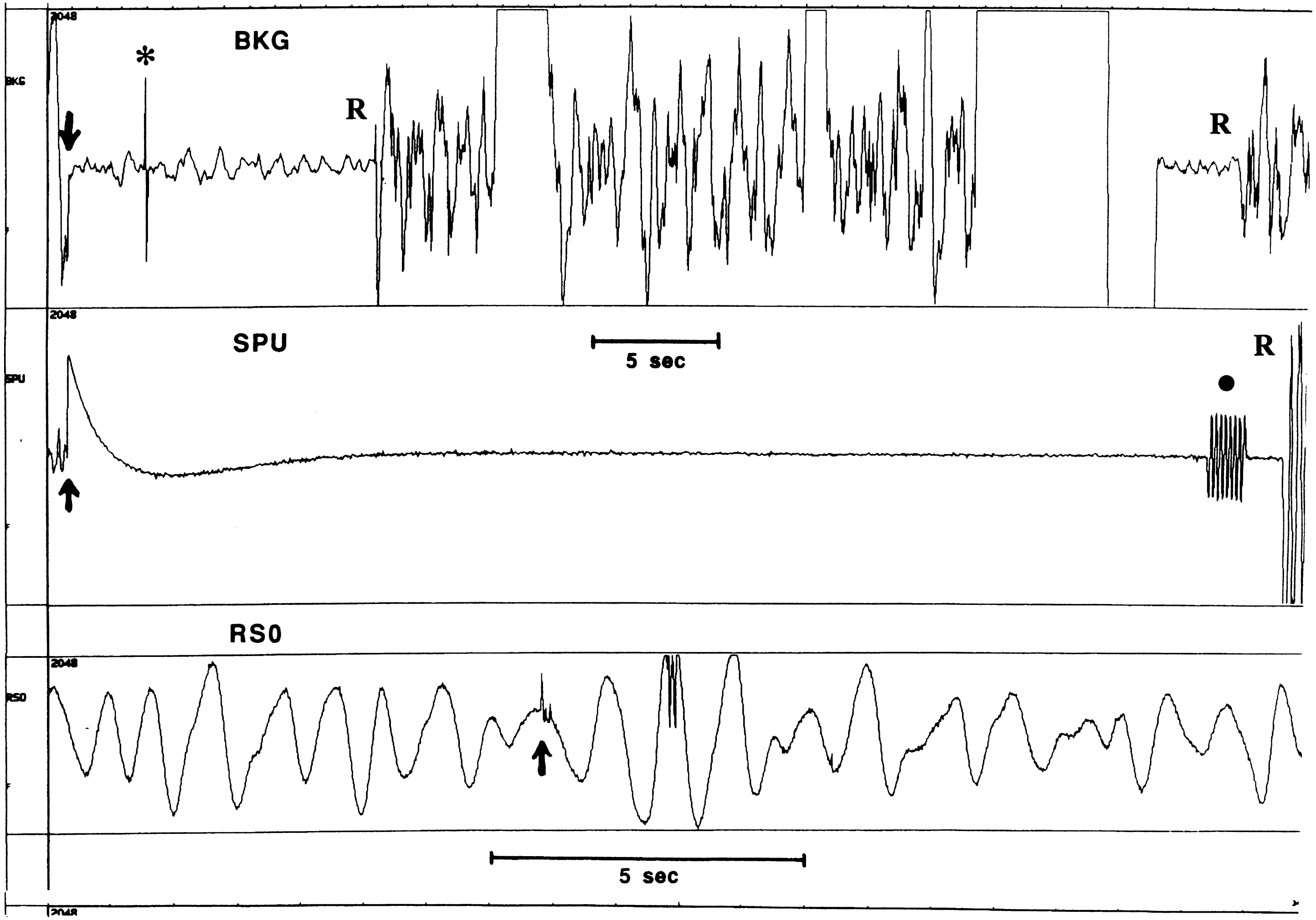
Fig. 4. Map showing Mt. Spurr seismic stations (solid dots) and cable lengths and orientations (lines extending from dots). Cable symbols extend from the electronics package (pre-amp, VCO, etc.) to the seismometer. The upper scale bar is for cable length and the lower scale bar is for the map (lower right corner of figure). Contours are at 500 m intervals. Station CRP was damaged by lightning during the August 18, 1992 eruption. Constant network stations are underlined.

reference signal (Fig. 5). The former is usually called 'gain ranging' or 'single gain ranging' and the latter 'super gain ranging' or 'double gain ranging.' When the signal becomes smaller, the gain ranging automatically turns off and the original scale is returned (Fig. 5, top and middle traces). Automatic gain control occurs in the VCO at the remote field sites, and the gain-ranged signal is then telemetered to the common collection point. Automatic gain control can only be produced at the VCO and cannot enter the data stream any other way.

Lightning, which produces a broadband electromagnetic pulse (Uman, 1987) propagating at the speed of light, appears on seismograms as simultaneous (same sample, or <0.008 s) gain ranging at several stations. Because gain ranging occurs only at individual sites, simultaneous gain ranging at stations separated by tens of kilometers must represent a signal

Fig. 5. Lightning signals at 02:17:22 UTC on August 18, 1992 recorded on three seismic stations. Arrows show time of lightning strike. Station BKG (top) went into single gain-range mode as shown by the single pulse at upper left (asterisk) 3 s after the lightning strike. The original scale returned at "R". Station SPU (middle) went into double gain-range mode (because of a stronger signal), as shown by the eight-cycle pulse at right (solid dot). The original scale returned at "R". A spike was recorded at station RSO (bottom), which does not have gain ranging. The strong background signal is volcanic tremor from the eruption. 50 s of data are shown for stations BKG and SPU, and 20 s are shown for RSO. Traces from BKG and SPU are aligned in time, whereas that from RSO is offset to the right. Maximum amplitude for each trace is 2048 counts.

MT. SPURR LIGHTNING STRIKE, AUGUST 18, 1992



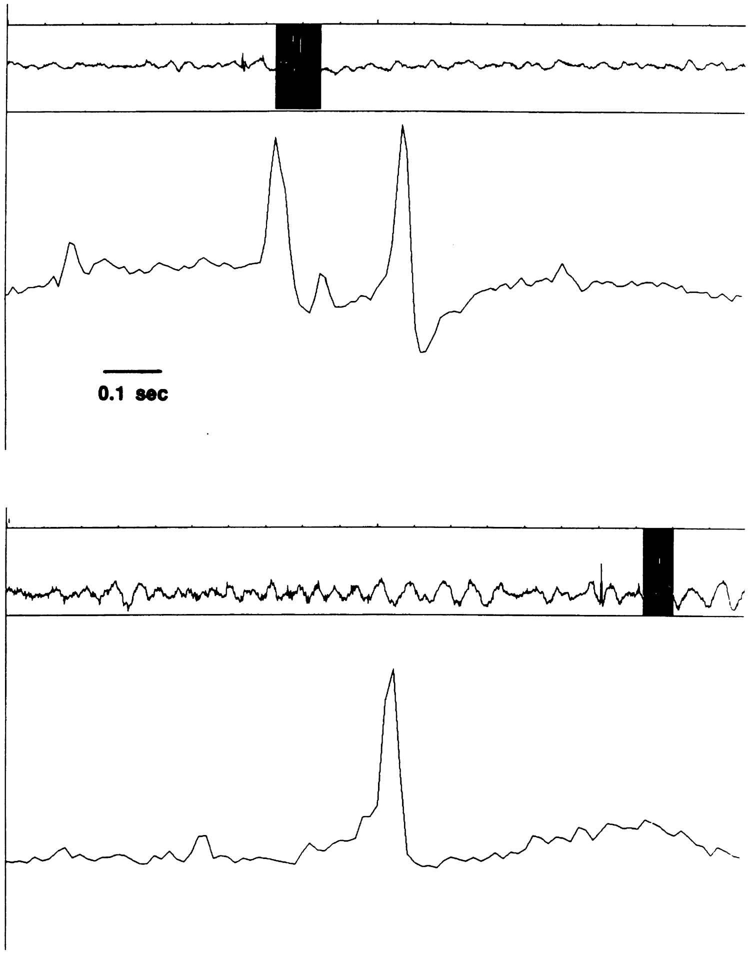


Fig. 6. Examples of lightning spikes at seismic station RSO, 90 km south-southwest of Mt. Spurr. Typical spikes were 0.04–0.05 s wide. Spikes include the entire response of the seismic system and should not be confused with lightning sources alone. Sample interval is 1/120 s. Upper trace of each pair shows 20 s of data; enlarged portion is highlighted in black. Top part show two spikes and bottom part shows one.

propagating at speeds much higher than any known seismic velocities. At more distant stations, or those without gain ranging, lightning often appears as spikes in the data (Fig. 6). RF interference or noise that exists on the telephone lines can also cause spikes in seismic data. However, noise, RF interference, and other non-lightning induced spikes can be identified by noting the following: (1) If the spikes that are produced on seismograms are from telephone noise, the spike will be recorded on all of the eight stations that are using that telephone line for data transmission. (2) The characteristic signature of the spike that is created by lightning is only observed during volcanic eruptions (or thunderstorms elsewhere; J. Lahr, personal communication, 1995). (3) Other types of known seismic noise are identifiable by noting that the signal is quasi-periodic in nature or tends to come in long duration bursts (Fig. 7). The combination of spikes and gain ranging at several stations simultaneously can only be caused by lightning or other electromagnetic phenomena.

Based on geometric arguments presented below, we believe the seismometer cable (which is shielded) is acting as the antenna which receives the electromagnetic wave created by lightning. Ward et al. (1974, p. 82) reached a similar conclusion: “Apparently electric

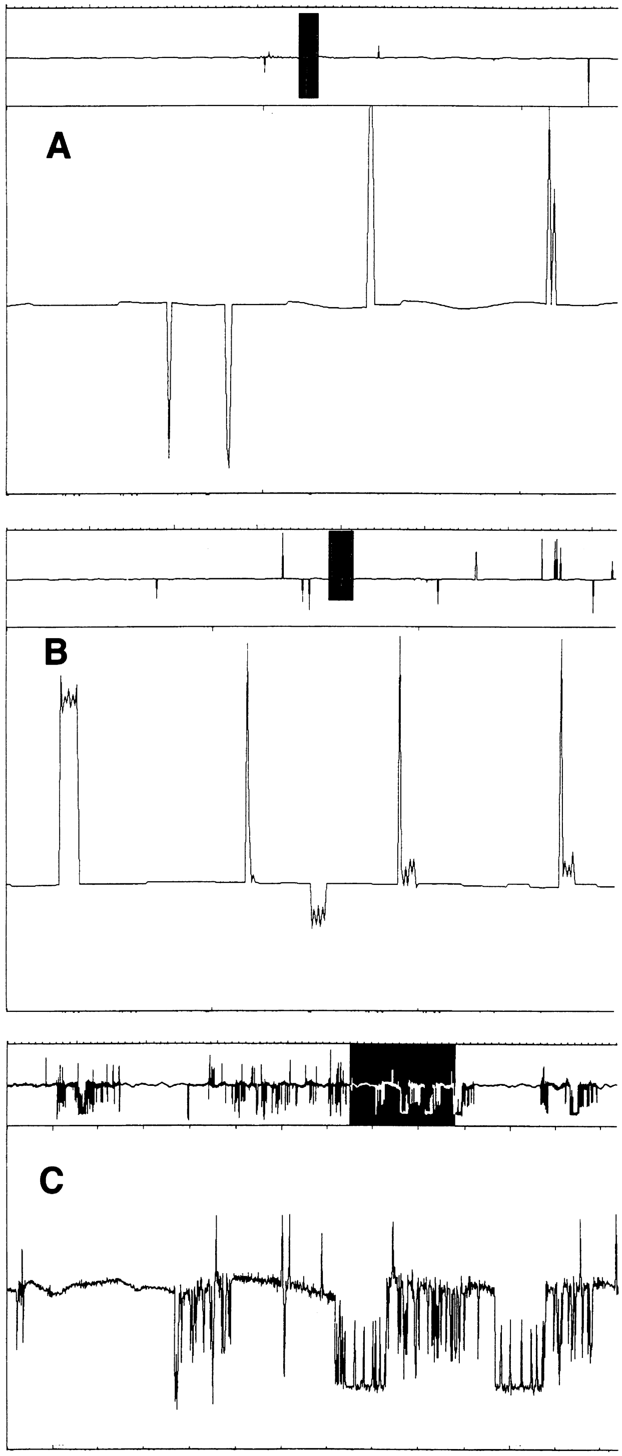


Fig. 7. Examples of non-lightning noise at several different seismic stations. Note the differences between these signals and those in Fig. 6: (A) 2 s of data; (B) 2.5 s of data; (C) 13 s of data. Upper trace of each pair shows 70–80 s of data; enlarged portion is highlighted in black.

Table 2
Mt. Spurr seismic station parameters

Station name	Distance (km) (to Crater Peak)	Elev. (m) a.s.l.	Azimuth from Crater Peak	Cable length (m)	Cable azimuth[a] from north	Comment
CRP	4.8	1622	87	13	23	Damaged by June 27 lightning
BGL	7.7		272	10	120	
CKL	9.1	1265	213	24	49	
CGL	13.6	1082	69	25	267	
SPU	13.8	800	132	19	110	
NOG	16.2	1244	17	16	320	S-shaped cable
BKG	21.7	1009	183	17, 8	183, 273	L-shaped cable
NKA	79.7	100	136	–	–	Regional station
SKN	88.3	564	25	–	–	Regional station
RS0	93.6	1921	198	–	–	Redoubt station
RS1	93.6	1864	198	400	–	Redoubt station
RS2	93.6	1953	198	400	–	Redoubt station

[a] Azimuth from electronics package to seismometer.

currents were being induced by local lightning in the 15 meter cable between the geophone and preamplifier." The geophone cable used at Spurr is known as "spiral-4," and is an insulated 4 conductor (14 gauge each) cable with strain-relief shielding; line resistance is negligible. Cable orientations are shown in Fig. 4 and Table 2. In most cases, the cable is buried a few centimeters or is lying on the ground surface. The seismometer is buried 0.5–1.0 m deep. The orientation of the seismometer is always vertical for the particular instruments (Mark Products model L4-C) deployed at Mt. Spurr. That is, the axis of the cylindrical seismometer coil is oriented vertically. An important issue is whether the coil or the cable is sensing the electromagnetic signal; our data favor the cable (discussed in detail below).

3. Analyses

We scanned all the continuous seismic data files for each eruption to search for and measure lightning flashes. We counted all events that registered as simultaneous spikes on three or more Spurr stations, or events that registered on a minimum of two Spurr stations where one of the stations went into a gain-ranging mode. Also, all events to be analyzed must have registered as a spike or gain ranging on the station RSO. This consisted of using a subset of stations that were operating during all three eruptions, which we deem a uniform or constant station network. The uniform event counts, which had stricter criteria, were always lower than the full counts. We found that the June and August eruptions had about the same number of inferred lightning flashes, and September fewer (Table 3). Based on comparison with the number of flashes recorded by the AVO lightning detection system in August, the seismic systems had a higher threshold (or were less sensitive). A similar comparison with the BLM data shows that the seismic systems were more sensitive. Apparently, the seismic systems are fairly low-sensitivity lightning detectors which have the advantage of being located very close to the lightning sources. A histogram (Fig. 8) shows the normalized number of flashes recorded at each seismic station for each eruption.

We measured amplitudes for spikes on station RSO, which is 90 km southwest of Mt. Spurr. This station was far enough away from the volcanic plume that the signals remained on scale, whereas amplitudes for closer stations were often saturated (clipped). Because of its gain and distance, RSO was the optimal station for this purpose. The amplitudes of the lightning flashes (spikes on station RSO) are displayed on a histogram in Fig. 9. It can be seen that, on average, the August lightning was strongest, September medium, and June weakest. We discuss possible artifacts of these measurements below.

Time histories of the lightning flashes are shown superimposed on volcanic tremor data in Fig. 10.

Table 3
Selected Mt. Spurr 1992 lightning parameters

Parameter	June 27	August 19	September 17
Total no. of strikes	61	57	7
Uniform no. of strikes	28	29	3
Mean amplitude, station RSO	880 cts	1400 cts	1000 cts
Timedelay from eruption onset	25 min	26 min	21 min
Eruption duration	4 h 03 min	3 h 28 min	3 h 36 min
Tephra volume[a]	44×10^6 m^3	52×10^6 m^3	56×10^6 m^3
Max tremor, reduced displacement[b]	16 cm^2	30 cm^2	25 cm^2
Max ash altitude[c]	14.5 km	13.7 km (18 km)[d]	13.9 km
SO_2 emitted (tons)[e]	200 ± 60 kt	400 ± 120 kt	230 ± 70 kt
Wind speed and direction[f]	80 km/h from S	60 km/h from NW	83 km/h from W
Air temperature[g]	51°F	57°F	38°F
Relative humidity[h]	92%	80%	69%

[a] Neal et al. (1995).
[b] Reduced displacement is rms amplitude multiplied by distance, hence units are cm^2 (McNutt et al., 1995).
[c] Measured from National Weather Service radar (Rose et al., 1995).
[d] Estimated from pilot report (Paskievitch et al., 1995).
[e] Bluth et al. (1995).
[f] Average of 18,000 and 23,000 ft wind data.
[g] National Weather Service, Anchorage.
[h] Calculated from data supplied by National Weather Service.

These plots reveal both similarities and differences. The June lightning occurred rather uniformly during the first 2.5 h of the eruption, followed by a gap, then a burst of lightning near the end of the eruption. The August lightning began with a single flash, then a gap, and then a strong burst about 1.2 h after the eruption onset. This was followed by a lull, then a burst near the end of the eruption similar to the one in June. There

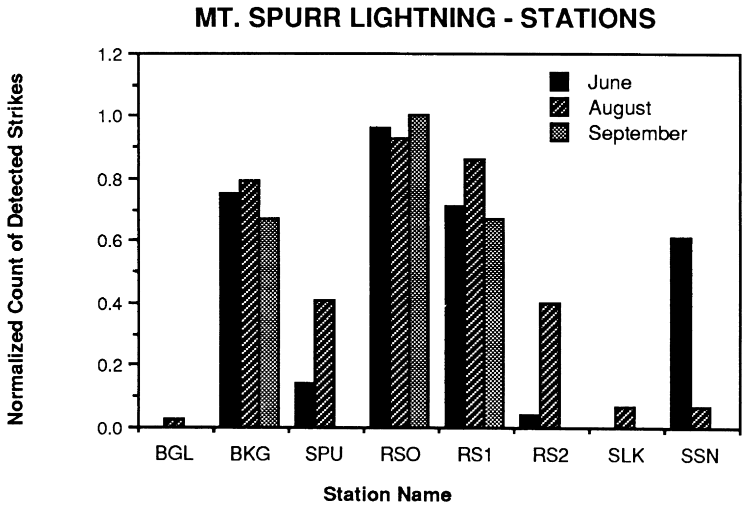


Fig. 8. Relative number of lightning strikes recorded at each seismic station for each of the three eruptions. Data are normalized between eruptions, not stations. Lightning was recorded similarly for all three eruptions at stations BKG, RSO, and RS1. However, note the difference in the number of strikes recorded at stations SPU, RS2, and SSN for the June and August eruptions. RS1 and RS2 are located a few hundred meters from RSO; other station locations are shown in Figs. 1 and 4.

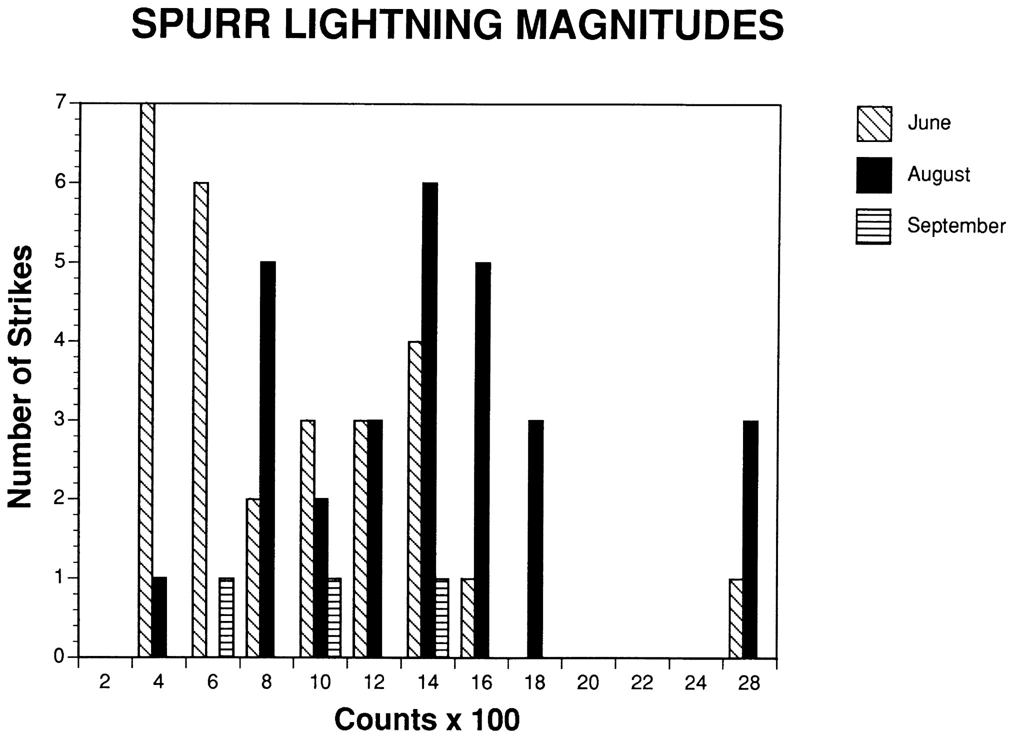


Fig. 9. Histogram of lightning magnitudes for the three eruptions. Magnitudes are the amplitudes in digital counts at station RSO. Note that on average August lightning was strongest, June weakest, and September intermediate. Only data meeting the uniform criteria are shown.

were only a small number of flashes for the September eruption, however, two flashes occurred near the beginning and two near the end; these two "bursts" were similar in timing to the other two eruptions.

In an attempt to understand the geometry of the lightning flashes, we made plots showing the number of spikes, single gain ranges, and double gain ranges for each eruption (Fig. 11). A double gain range indicates the strongest signal (for stations that have this feature), a single gain range, a relatively medium strength signal, and a spike of relatively weak signal. Using this information, along with known plume directions (Fig. 12; Alaska Volcano Observatory, 1993) and measured seismometer cable orientations (Fig. 4), enabled us to infer geometric orientations for some of the lightning flashes.

4. Results

Our first and most basic result is that lightning occurred during all three of Mt. Spurr's eruptions in 1992. In each case there was a time delay of 21–26 min from the beginning of the eruption to the first recorded lightning flash (Table 3). This is longer than the 5–15 min noted for Redoubt Volcano by Hoblitt (1994). The June and August eruptions had the highest number of flashes and September much lower based on uniform data from the constant station network (Table 3). The August lightning was strongest based on the station RSO amplitudes, with September medium and June weakest; the difference between August and June was nearly a factor of two (Table 3 and Fig. 9). The differences in numbers of single and double gain ranges and the differences in stations for the three eruptions suggest that there were azimuthal variations which probably correlated with the wind directions and eventual ash footprints (Fig. 12).

Data in Fig. 8 show that June lightning was recorded more often at station SSN, the same at BKG, RSO, and RS1, and less often at SPU and

RS2 than August lightning. June ash (and presumably lightning) traveled to the north and August ash to the east southeast (Fig. 12). Note that the lightning was not simply recorded preferentially at stations in the same azimuths as the ash clouds. Rather, the cable orientations (Fig. 4) are strongly correlated. For example, the SPU cable is parallel to the August ash cloud; the August lightning was recorded more often and more strongly on this station than June lightning. Station BKG has an 'L' shaped cable, with its two arms oriented north–south and east–west, subparallel to the June and August eruptions, respectively. Lightning was recorded equally as often for the June and August eruptions on this station. These facts suggest that the seismometer cable is acting as the sensor, rather than the seismometer itself, which would be omnidirectional in the horizontal plane.

The azimuthal differences and the fact that some lightning was recorded on the Bureau of Land Management (BLM) system suggest that both IC and CG lightning occurred. The vertically oriented CG lightning was likely recorded by the BLM system preferentially because the BLM antennae and systems were favorably tuned to record this lightning. The lightning strikes recorded by the BLM system during the August eruption were not the strongest or highest amplitude lightning flashes (Table 4 and Fig. 9), so we rule out amplitude alone as the reason for the recording on the distant BLM stations. It is possible that the lightning recorded on the BLM system occurred higher in the eruption column (one pilot report places the top of the eruption column at 18 km, higher than June or September), but we have no other data to resolve this issue.

The BLM data, which also recorded polarity, showed that lightning was negative at first, then positive (Table 4). By convention (Uman, 1987), negative lightning lowers negative charge to the ground and positive lightning lowers positive charge to the ground, for CG lightning. Thunderstorms (Uman, 1987) and eruptions at Redoubt (Hoblitt, 1994) both show the same sequence of first negative, then positive lightning. This is interpreted to demonstrate a separation of charge based on particle size, where, after collision between particles, positive charge is preferentially stored in small particles and negative charge in larger ones (e.g. Illingworth, 1985). Since larger particles are found near the base of a cloud, negative charge is lowered first. Then either the large particles fall out, taking their charge with them, or the charge distribution changes within the cloud as a result of the initial negative lightning strikes. For volcanoes there is a second possible explanation for the charge distribution: volcanic aerosols may increase the number of small particles or may preferentially carry positive charge. Lane and Gilbert (1992) found that aerosols carried positive charge and ash particles negative charge at Sakurajima. Independent data from the TOMS satellite (Bluth et al., 1995) show that the August eruption of Spurr had twice the SO_2 of the June eruption (Table 3). Considering that SO_2 plus water forms a common aerosol, this fact helps to explain the stronger lightning during the August eruption. Andesite magmas generally contain about 4 wt.% water, thus it is also possible that ice particle formation played a role, especially if the ash column height was greater. However, we have no direct data on either ice or water content of the ash column.

The three Spurr eruptions in 1992 had similar durations, tephra volumes, and plume heights (Table 3), so there is no obvious correlation between lightning and these parameters. However, volcanic tremor peak amplitude and the amount of SO_2 both do correlate with the strength of the lightning (Table 3 and Fig. 10). Further, the rate of increase of tremor amplitude was most rapid for the August eruption. All these observations suggest that the August eruption was the most gas-rich and hence the most explosive. The greater explosivity would have created more small ash particles, or conversely the extra gas itself could form aerosols. Either case would permit greater charge separation, which is in agreement with the stronger lightning during the August eruption.

The above observations help explain the differences between lightning observed during the June and August eruptions. While the strength of the September lightning is intermediate between these two, the number of flashes is much lower (Table 3). We believe differences in temperature and humidity may explain this discrepancy. The September eruption occurred on the coldest and driest day of the three eruptions (Table 3). Noting that most thunderstorms occur during hot, humid weather, we suggest that the small number of flashes in September may reflect the slightly lower electrical conductivity of the relatively cold dry air.

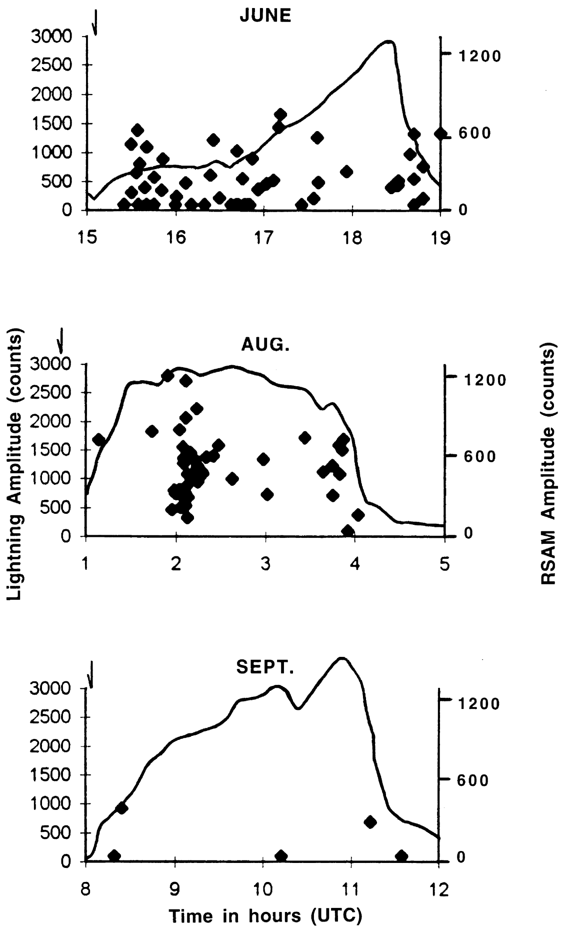


Fig. 10. Volcanic tremor amplitude (continuous curve, right scale) and lightning strikes (dots, left scale) as a function of time for the three eruptions on June 27, August 18, and September 17, 1992. The intensities of the eruptions are roughly proportional to the tremor amplitudes. Lightning strikes are shown as dots, with height proportional to amplitude on station RSO. Note the different vertical scales for the lightning. RSAM stands for Real-time Seismic Amplitude Measurement. Arrows show eruption onsets.

Alternatively, the different conditions may have permitted or not permitted the formation of ice particles. We thus infer that the flashes are occurring between charged ash cloud constituents or between the ash clouds and the surrounding air, although we have no further data to address this issue.

An additional possibility is that wind speed played a role. Wind causes ash clouds to disperse, hence strong winds will disperse the charged particles faster than light winds. In order to produce lightning, certain charge densities are required. Then, assuming that the system behaves like a capacitor (the first and most simple approximation) where charges are separated, the potential difference between the two "plates" or charged regions, depends on the distance, charge, dielectric constant, and size of the "plates". The August eruption occurred during the lightest winds, which probably means that, other things being equal, the charge densities were highest and separation distances lowest for this eruption. Further, lighter winds mean the eruption column is more vertically oriented; this may have allowed greater vertical charge separation. Thus, the August eruption may have produced more CG lightning than the other two, which would agree with the BLM and AVO lightning detection system data.

There are also geologic factors to consider. The August eruption produced two distinct tephras: first, a tan layer, pumiceous, moderately well sorted and reversibly graded (layer A; Neal et al., 1995), then a dark gray layer, andesitic, well sorted and ungraded (layer B). Layer B was, on average, denser by about 30%, and finer grained at any given distance from the vent (Neal et al., 1995). These facts suggest greater explosivity (larger and more frequent explosions produce finer ash) and greater loss of gas. Lightning from the August eruption mainly occurred during a burst of activity about 1 h after the start of the eruption. We suggest that this period of intense lightning marked the onset of eruption of layer B. Similarly, the bursts of lightning noted near the end of each eruption (Fig. 10) suggest that the explosivity decreased (less expanding gases) as the eruptions waned, changing the charge distribution.

5. Discussion and conclusions

Using all available data we have documented the occurrence of lightning during all three of Spurr's 1992 eruptions and measured its characteristics. We found that the August lightning was strongest, September medium, and June the weakest, whereas the number of flashes was about the same for June and August and an order of magnitude lower for September. All three eruptions had similar durations, tephra volumes, and plume heights, but occurred during different meteorological conditions. These

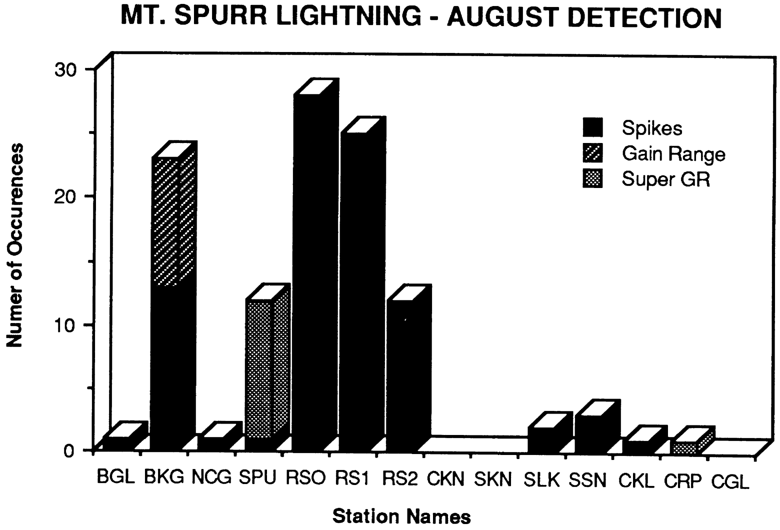


Fig. 11. Summary plot of the number of occurrences of spikes, gain-ranges, and super gain-ranges at each station for the August 18, 1992 lightning. In general, spikes are most common, followed by gain-ranges and super gain-ranges. Only data meeting the uniform criteria are shown.

facts together suggest that volcanic lightning is caused by charge separation in the erupting ash column, modulated by the existing environmental conditions, such as wind, temperature, and relative humidity. Therefore, we found that the number of lightning flashes alone did not correlate well with the size of eruption, in contrast to the results of Hoblitt (1994) for Redoubt Volcano. Instead we found that the *amplitude* of lightning correlated better with eruption parameters (Table 3). For comparison, thunder clouds show a correlation between cloud size and number of flashes (Williams, 1985).

The delay time between the start of the eruptions and the first lightning was 21–26 min. This is about 2–5 times longer than at Redoubt (Hoblitt, 1994). We note that the composition of Spurr's tephra is andesite, whereas Redoubt's is more silicic dacite, hence we speculate that higher silica content (and possibly particle shape) is more efficient at storing and carrying electrical charges. The BLM data for Spurr's August eruption showed first negative, then positive lightning (Table 4). This is similar to lightning at Redoubt (Hoblitt, 1994) and in most thunderstorms (Uman, 1987), suggesting that similar processes of charge separation based on particle size are occurring (e.g. Illingworth, 1985). Unlike thunderstorms, volcanic eruptions retain information about particle size distributions in their ash deposits. These may make eruptions good candidates for general lightning research. The differing ash characteristics (layers A and B) of the August eruption suggest that lightning reflects ash source processes because atmospheric conditions remained constant over the three and a half hours of the eruption.

It is important to remember that Spurr's lightning was recorded by seismometers accidentally. Indeed, electronics technicians spend considerable time trying to isolate seismic systems from potential noise sources including lightning. The importance of doing this was underscored by the fact that station CRP (Fig. 4) was disabled by a lightning strike during the August eruption. Nevertheless, our results show that seismometers and their cables may be better at recording IC flashes (horizontal as well as vertical) than some commercial lightning detection systems. Because of their close proximity to volcanoes, seismic systems may be more sensitive than distant lightning detection systems. Also, there may well be small-scale discharges earlier that go undetected.

All the results presented here suggest that the detection of lightning would be helpful as a component of a warning system to detect volcanic ash clouds. Such a system might be composed of seismometers to record earthquakes and volcanic tremor, barographs or

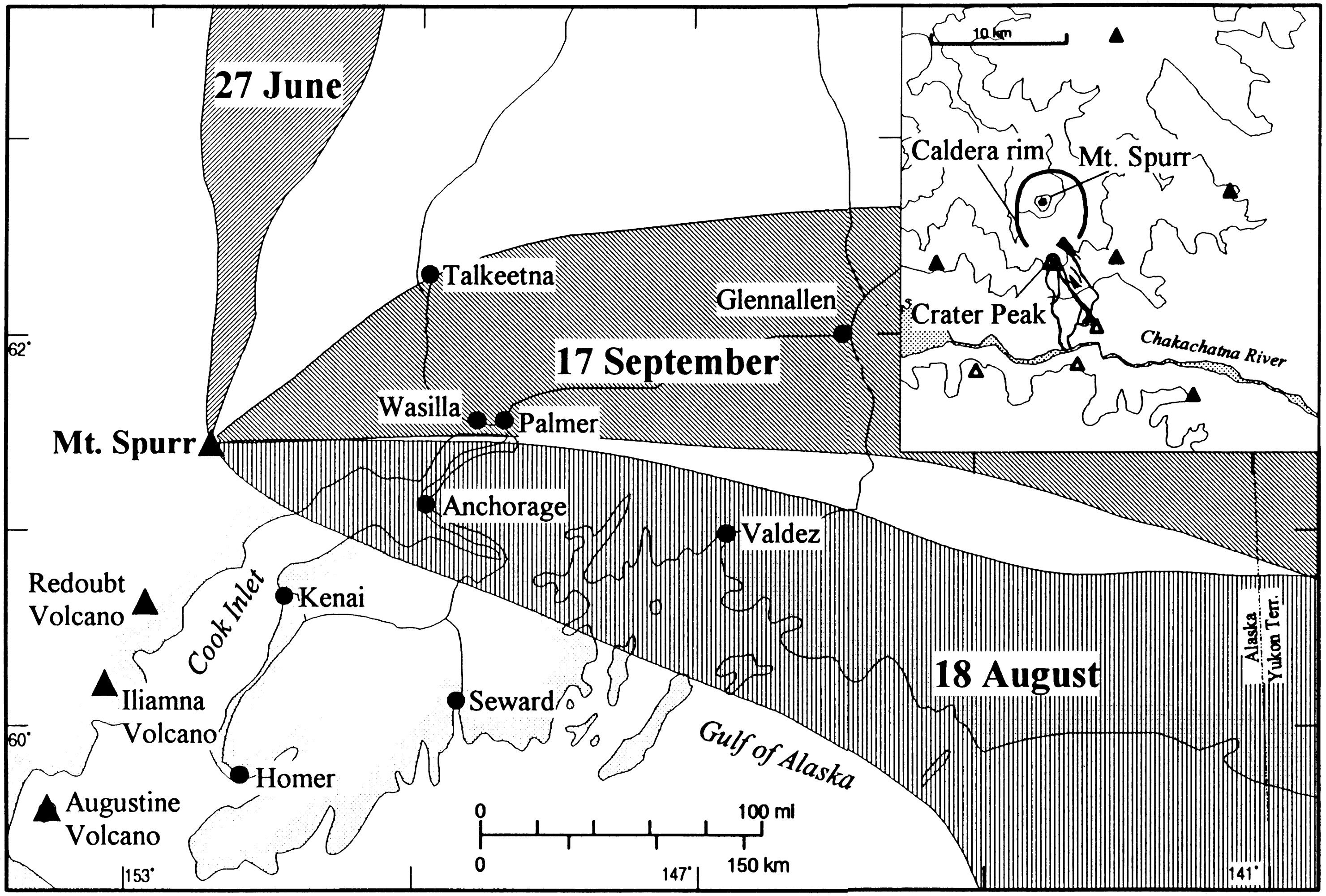


Fig. 12. Map of the ash distribution for the three eruptions of Mt. Spurr in 1992. The three eruptions sent plumes in different directions because of different prevailing winds. Wind speeds are shown in Table 3. Inset shows detail of summit region (see also Fig. 4).

Table 4
Simultaneous lightning strikes recorded on BLM lightning detection system and Mt. Spurr seismograms, August 18, 1992

BLM time[a]	Seis. time[b]	Time diff.[c]	BLM station[d]	AVO station[e]	BLM magnitude[f]	Comment
17:43:42.73	17:44:06.45	23.72	6, 5	SPU, BKG,[g] RS0, RS1	−134.1	
17:59:21.04	17:59:44.79	23.75	7, 6, 5, 1	SPU, RS0, RS1	−95.2	
18:04:38.62	18:05:02.33	23.71	6, 5, 3, 9, 4	RS0, RS1	−118.5	
18:06:20.71	18:06:44.46	23.75	7, 6, 5, 1, 9, 11	RS0, RS1, RS2, SSN	−216.4	Strongest BLM negative value
18:07:26.21	18:07:49.96	23.75	7, 6, 5, 3, 1, 9	RS0, RS1	−71.4	
18:09:20.32	18:09:44.07	23.75	7, 6, 9, 1	BKG, SPU, RS0, RS1, RS2	−90.2	
18:13:28.02	18:13:51.77	23.75	7, 6, 5	RS0, RS1	−73.8	
18:14:15.26	18:14:39.01	23.75	7, 6, 9, 1	SPU, BKG,[g] RS1, RS0	−80.9	
18:16:58.54	18:17:22.27	23.73	6, 5, 1, 9, 4	BKG, SPU, RS0, RS1, RS2	−149.3	This event is shown in Fig. 5
18:24:40.01	18:25:03.73	23.72	6, 1	RS0, RS1	−87.7	
18:37:26.86	18:37.50.62	23.76	7, 6, 5	BKG,[g] RS0, RS1	−90.9	
19:51:57.80	19:52:21.56	23.76	7, 5	BKG, RS0, RS1, RS2	+279.1	Strongest value; only BLM positive value

[a] Relative time from BLM, Alaska Daylight Time (ADT).
[b] Satellite-based true time (ADT); measurement error ±0.03 s.
[c] Time drift of BLM clock and measurement error are probable reasons for variation in time difference values.
[d] Stations listed in order of decreasing magnitude.
[e] RS0, RS1, RS2 and SSN show only lightning spikes—not gain ranging.
[f] Relative magnitude (average) measured using all triggered BLM stations; arbitrary units.
[g] Station BKG showed a spike only; BKG listed without superscript indicates gain ranging.

microphones to record acoustic signals, and lightning detectors. The near simultaneous occurrence of all three types of signals, factoring in delay times caused by wave propagation and charge separation, would be persuasive evidence that an explosive eruption was in progress. Studies of lightning frequency of occurrence and strength may eventually prove useful to help estimate the size of eruptions, as has been done for volcanic tremor (McNutt, 1994). In general, volcanic lightning is important because it can help confirm that eruptions are in progress, although the information may be limited by the long delay from eruption onset to first lightning and the variability of eruptive and atmospheric conditions.

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