Observations of Lightning Flash Energy Spectra in a Volcanic Eruption Column

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ABSTRACT: Lightning mapping observations of volcanic lightning from the 2009 eruption of Redoubt Volcano, Alaska, USA, have been used to calculate lightning flash energy spectra. The formulation of the flash energy spectrum was determined from dimensional arguments recently developed by *Bruning and MacGorman* [2013], who postulated that the kinematic and electrical components of thunderstorms are coupled via advection of charged precipitation. The Redoubt eruption consisted of a series of distinct explosive eruptions that differed in duration and eruption column height allowing for comparison of flash energy spectra between eruptive events with varying energy input. The duration of infrasound produced by the expulsion and jetting of volcanic ejecta is used as a proxy for kinematic energy input into the eruption column. The transition from high turbulent forcing by the eruptive jet to less-turbulent motions can be examined because each infrasound event ends relatively abruptly. The data show an evolution in the spectral shape of flash energy that correlates with different phases of eruption column evolution. For example, during the period of initial eruption column ascent the peak in flash energy typically occurred at small flash sizes. Following termination of energy input into the eruption column the peak shifted to larger flashes sizes, which would be expected to occur as turbulence subsides. These results show that changes in lightning length scales reflect changes in the kinematic structure of volcanic eruption columns, supporting the hypothesis that kinematic and electrical energy are linked.

INTRODUCTION

The relationship between the kinetmatic and electrical energy in a thunderstorm was recently studied by *Bruning and MacGorman* [2013], who analyzed lightning flash energy spectra for two supercell thunderstorms that occurred in 2004 in Oklahoma. *Bruning and MacGorman* calculated energy spectra using an energetic scaling that combines flash rate and flash area and found a consistent 5/3 power law over flash length scales of several km with a peak in flash energy at 10 km. Both the peak flash energy and the length scales over which the 5/3 power law was observed are similar to what is expected for the inertial subrange of kinetic energy spectra for thunderstorms. This correlation suggests that the kinematic and electrical properties of thunderstorms are linked through the advection of charged precipitation.

Here we extend the analysis of lightning flash energy to electrical activity that occurs in volcanic eruption columns. Lightning is known to occur in the plumes and ash clouds produced by explosive volcanic eruptions over a wide range of eruption magnitudes [*McNutt and Williams*, 2010]. There are several mechanisms that contribute to plume electrification [*Mather and Harrison*, 2006; *James et al.*, 2008], such as fracture of silicate particles [*James et al.*, 2000], collisional charging of silicate particles [*Houghton et al.*, 2013], and collisional ice-contact charging analogous to that of thunderstorms [*Williams and McNutt*, 2005]. It is believed that volcanic ejecta are charged upon eruption due to the fracture mechanisms, and collisional processes charge the plume after eruption.

Similar to a thunderstorm, an explosive volcanic eruption provides a source of energy for convection of a turbulent plume. Lightning is evidence that some of the kinematic energy in a plume or cloud has

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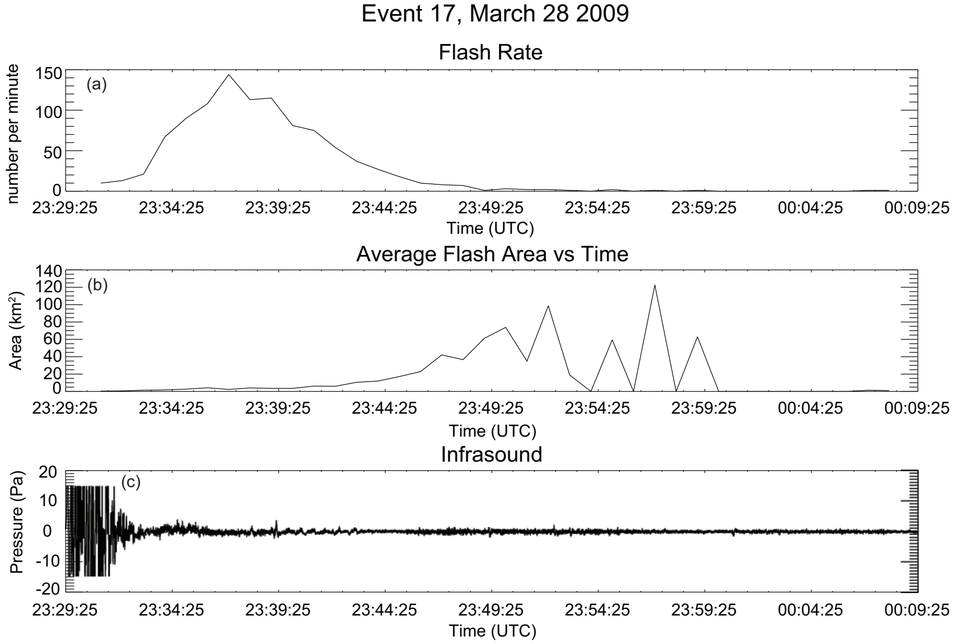

Figure 1: Time series of (a) flash rate, (b) average flash area, and (c) infrasound for event 17 of the Redoubt eruption. This explosive event began at 23:29:25 UTC as determined from the infrasound data and was relatively short, with acoustic duration of 3 minutes. Peaks in flash rate and flash size are anti-correlated.

been converted into electrical potential energy. Lightning flashes represent consumption of that potential, and their sizes and rates reflect the textural organization of that potential. Differences in energy input into the plume are expected to affect the character of electrical activity. For example, more available energy is expected to lead to higher flash rates and smaller flash sizes due to an increase in turbulence.

In this work we compare lightning flash energy spectra from lightning mapping data obtained during the 2009 eruption of Redoubt Volcano with low-frequency acoustic data (referred to as infrasound) collected during the distinct explosive events to show how inferred changes in the kinematics of an eruption lead to changes in electrical activity. We use infrasound as a proxy for the kinematic energy. Infrasound can be produced by several processes during a volcanic eruption such as explosions, pyroclastic density currents, and turbulence in volcanic jets [*Fee and Matoza*, 2013]. Thus, the duration of an infrasound signal during an explosive event represents a proxy for the duration of maximum input of energy into the plume.

DATA AND METHODS

Lightning mapping data were obtained by a 4-station lighitng mapping array (LMA) that was deployed approximately 80 km east of Redoubt. Data were collected throughout the duration of the eruption, which consisted of a series of distinct explosive events over a two-week period. The peak plume height of any of the explosive events was 19 km. During the larger explosive events of the Redoubt eruption, relatively short-lived (20-70 minutes) lightning storms occurred in the plumes with flash rates on the order of 100 discharges per minute. Due to the geometry of the LMA stations, only 2-D data were obtained, with location uncertainties of less than 200 meters for VHF sources located within a 50 km radius of Redoubt.

Flash energy spectra were calculated following the method of *Bruning and MacGorman* [2013] using

$$E(l) = \frac{A_h \eta^2}{l_w}, \tag{1}$$

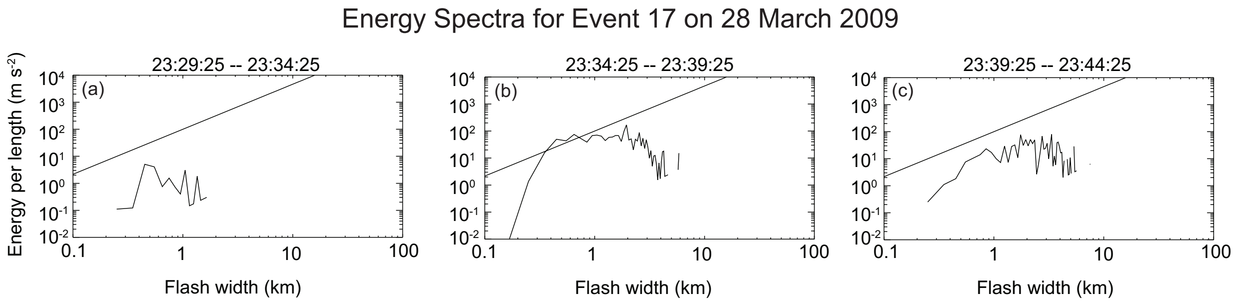

Figure 2: Energy spectra for the first 15 minutes of electrical activity for event 17, shown in three 5-minute time intervals. A line with a 5/3 slope is shown for comparison. The flash rates during the succeeding time intervals were not large enough to have meaningful spectra.

where A_h is the area of the convex hull of the plan-position projection of the VHF sources that make up a flash, η is the rate of flashes at length scale $l = \sqrt{A_h}$, and l_w is the bin width used to calculate the flash rate. A flash algorithm was used to group the VHF sources into flashes [*Behnke et al.*, 2013] and only flashes that contained 10 or more sources were used in the analysis.

Infrasound data (acoustic pressure) were recorded at a site 12 km north-northeast of Redoubt's summit [*McNutt et al.*, 2013]. The duration of an explosive event as determined from the infrasound data is used to indicate when the volcano was actively erupting and and was thus providing an input of energy. The infrasound duration was measured as the time from which the signal amplitude was twice that of the noise level to when it returned to the noise level.

Plume height data were obtained by a mobile C-band radar deployed approximately 80 km east of Redoubt during the 2009 eruption [*Schneider and Hoblitt*, 2013]. The radar made PPI sector scans throughout the duration of the eruption. Uncertainties in plume height are 2.3 km.

RESULTS

The electrical activity during an explosive event was characterized by peaks in flash rate and average flash size being anti-correlated; typically when flash rates were relatively high, average flash size was relatively low and when average flash area was relatively high, flash rate was relatively low, as predicted by *Bruning and MacGorman* [2013]. A representative example of flash rate and average flash size for one of the distinct explosive events (event 17) of the Redoubt eruption is shown in Figure 1. This event was relatively short, with acoustic duration of 3 minutes. The flash rate peaked approximately 5 minutes after the end of the explosive event. The average flash area was low for the first 10 minutes following the onset of the explosive event and began to significantly increase as the flash rate subsided.

While lightning activity lasted for a few tens of minutes after a large explosive eruption, the shape of the energy spectrum changed as the plume evolved. For example, the energy spectrum for the first 5 minutes of electrical activity for event 17 (Figure 2a) shows a peak in flash energy between flash width of 0.4 and 0.5 km, with only a narrow range of flash width present. During this interval the infrasound signal returned to background levels, indicating the end of explosive activity. In the next 5-minute interval, a wider range of flash width occurred, and overall the spectrum was flat between flash widths of 0.4 and 3 km (Figure 2b). During this interval the plume height reached its peak altitude of 12.7 km at approximately 23:37:09 UTC. This interval also coincides with the peak in flash rates. During the following interval (Figure 2c), when flash rates declined and average flash size increased, the spectrum best approximated a 5/3 slope. The peak in flash energy occurred at flash width of approximately 2 km. Because the infrasound data indicate that there was no further energy input into the plume at this time and the plume height had already reached it's peak, we infer that turbulence in the plume was subsiding during this time period.

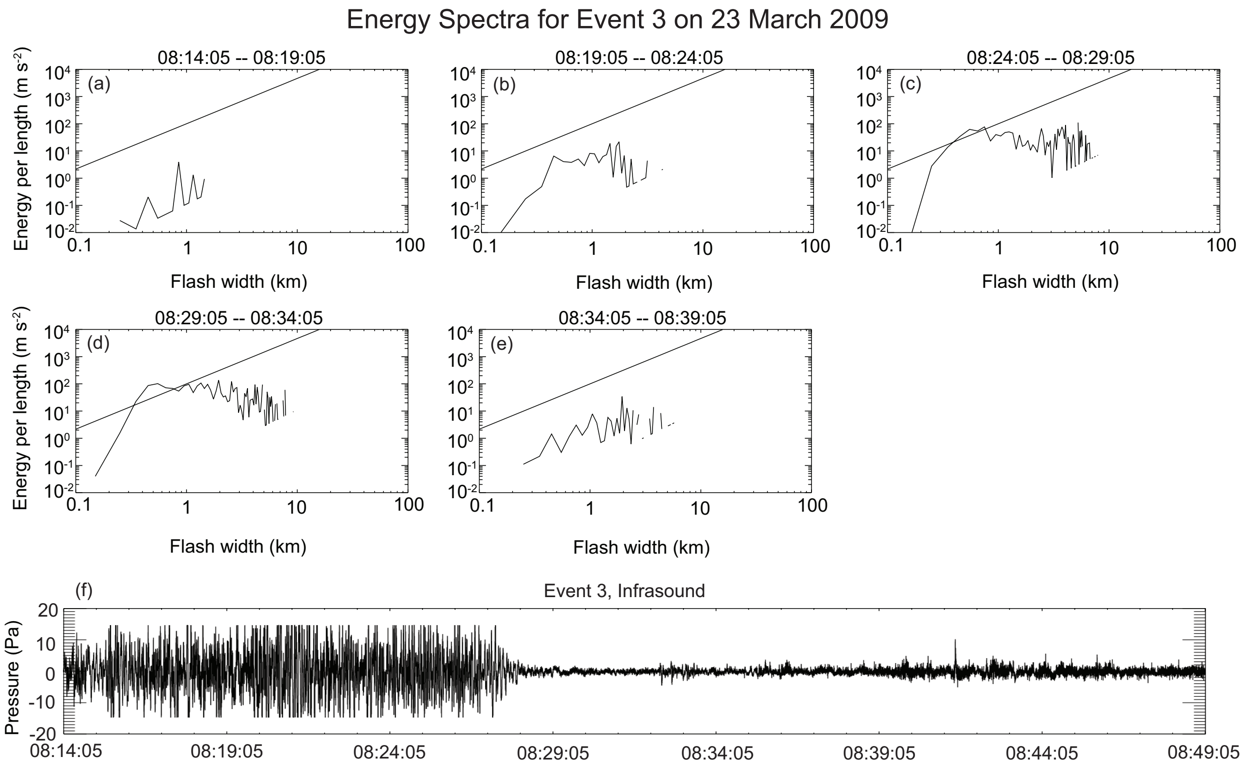

Figure 3: (a–e) Energy spectra for the first 25 minutes of electrical activity following the onset of explosive event 3 on 23 March 2009, shown in 5-minute intervals. A 5/3 slope is shown for comparison. (f) Infrasound recorded during event 3. Infrasound duration was 13 minutes.

The overall pattern shown in Figure 2 was observed during every large explosive event, though there were some differences in the spectra due to the differences in the duration of the explosive event. Figure 3 shows an example of the energy spectrum for an event that had a relatively long duration (13 minutes). The plume height peaked at 08:22:12 (UTC) (corresponding to Figure 3b). Again, the spectra show that, initially, only small flashes occurred (Figure 3b). As the range of flash width increased, the peak in flash energy remained at small flash size (Figure 3c–d), likely because the explosive activity was still ongoing, creating a source of energy input and turbulence in the plume. The infrasound signal returned to background at approximately 08:28:00 (Figure 3c) and the transition to a 5/3 spectral shape occurred at 08:34:05 (Figure 3e); the length of the time delay between the end of explosive activity to when the spectra take on a 5/3 slope is similar to that for event 17 (Figure 2) and the other large explosive events.

DISCUSSION AND CONCLUSIONS

Our results show that the length scales of flashes and peaks in flash energy are related to the duration of the infrasound signal produced during a distinct explosive event. When infrasound was produced, the peak in flash energy occurred at small flash size. After the infrasound signal returned to background levels, the peak in flash energy shifted to larger flash sizes.

We interpret this transition to be due to the changing kinematic structure in a plume. Initially, a plume is turbulent and convective as it ascends through the atmosphere. Once the input of volcanic ejecta into the plume ceases and after the plume reaches neutral buoyancy, turbulence in the plume will subside. Turbulence restricts the size of flashes by creating localized pockets of charge. As turbulence subsides, flashes become larger. These results support the hypothesis of *Bruning and MacGorman* [2013] that electrical and kinematic energy are linked.

That the transition to the 5/3 spectral shape occurred only toward the end of each event is somewhat contrary to the findings of *Bruning and MacGorman* [2013], who found a relatively persistent shape to their thunderstorm spectra. It could be that a spectrum was present at smaller length scales, but the LMA did not produce sufficient numbers of detections with the necessary spatial resolution at such small scales. Alternatively, perhaps the nature of the volcanic forcing was responsible for the differences. The turbulent forcing was highly impulsive in nature and of short duration, while the supercells they studied were in a steady state. The 5/3 spectrum represents an equilibrium where energy transfer is from an energy-maximum integral length scale down through the inertial range. Therefore, we would expect to see non-5/3 spectra where the convective system was still coming to equilibrium. If the turbulence-lightning hypothesis is correct, the eruption onset represents impulsive forcing, possibly at some small scale (below 1 km) that could have still been equilibrating at the time the forcing abruptly ended. This abrupt transition from forcing to dissipation would necessarily pass through an equilibrium state as the turbulent forcing relaxed and dissipative forces began to dominate. Any residual forcing would have been at larger scales for some short time while buoyant convective motions due to residual heat in the plume continued to force weaker vertical motion.

The presence of lightning activity with similar spectral shapes in both volcanic and thunderstorm convective plumes suggests that the convective action is a common organizing principle. This study further suggests that transitions between smaller and larger characteristic intergral length scales in thunderstorm activity should show corresponding shifts in the energy size spectrum.

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