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Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano

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ABSTRACT

Observations of volcanic lightning during the eruption of Redoubt Volcano in March and April 2009 were made with the Lightning Mapping Array. During the eruption twenty-three distinct episodes of volcanic lightning were observed. Electrical activity occurred as either a volcanic lightning storm with up to thousands of lightning discharges or as a weak electrical event with only a handful of lightning discharges. During the volcanic lightning storms we observed two phases of electrical activity: the explosive phase and the plume phase. The explosive phase consisted of very small discharges (on the order of 10–100 m) occurring directly above the vent while an explosive eruption was ongoing, whereas the plume phase was comprised of discharges occurring throughout the plume subsequent to the explosive eruption. The area of discharges during the explosive phase ranged from less than 1 km^2 to 50 km^2 or more. The electrical activity at the beginning of the plume phase was dominated by small discharges. Over time the horizontal extent of the flashes increased, with the largest flashes occurring at the end of the plume phase. The distribution of the horizontal size of the discharges over the lifetime of the storm indicate that the charge structure of the plume evolved from a complex and 'clumpy' structure to a more simple horizontally stratified structure. Plume height was shown to be a key factor in the quantity of lightning in a storm. The volcanic lightning storms occurred in plumes with column heights greater than 10 km. The tall plumes may contribute to the efficiency of charge generation through ice collisions by providing strong updrafts from the large thermal energy input from the eruption.

1. Introduction

Lightning is an inherent feature of many types of volcanic eruptions (McNutt and Williams, 2010), but it is not well understood how the characteristics of an eruption (e.g., plume height, temperature, magma composition, ash or gas content) influence the resulting electrical activity. The relationships between lightning and eruptive activity have recently been explored by some researchers (Hoblitt, 1994; McNutt and Davis, 2000; Bennett et al., 2010) using instruments that primarily detect the signals from cloud-to-ground lightning, while others (Thomas et al., 2010) have used methods that look at all the electrical activity in a plume including cloud-to-ground and intracloud lightning. Observations of so-called 'total lightning' are possible with the Lightning Mapping Array (LMA) (Rison et al., 1999; Thomas et al., 2004), which locates sources of VHF radiation that are produced from lightning as it propagates. The LMA effectively provides a map of all of the electrical activity in a plume, making detailed studies of volcanic lightning and its relationships to eruptive activity possible.

The LMA was previously used to study lightning during the 2006 eruption of Augustine Volcano, also in Alaska, which characterized the styles and types of electrical activity that occurred as a result of the eruption (Thomas et al., 2007; Thomas et al., 2010). One of the main results of the Augustine Volcano study was that lightning occurred in two distinct phases, an explosive phase and a plume phase. The explosive phase described electrical activity observed during the actual explosive event, while the plume phase described lightning that occurred in the plume subsequent to the explosive eruption. Additionally, lightning during the Augustine Volcano eruption was classified into three categories: vent discharges (small, 10–100 m, high rate discharges close to the vent), near-vent lightning (medium sized, 1–7 km discharges extending from the volcano into the eruption cloud) and plume lightning (large sized, 10 km or more, branched discharges similar to intracloud (IC) lightning observed in thunderstorms).

More recently, the LMA was used to study lightning during the eruption of Redoubt Volcano, located in south-central Alaska (Fig. 1). Redoubt Volcano underwent a series of explosive eruptions in late March and early April of 2009, most of which produced substantial electrical activity. The major events occurred between 23 March and 4 April, 2009, though the full period of explosive activity extended through April 5. Peak plume heights for each explosive event ranged from 5 to 19 km, and the entire eruption was classified

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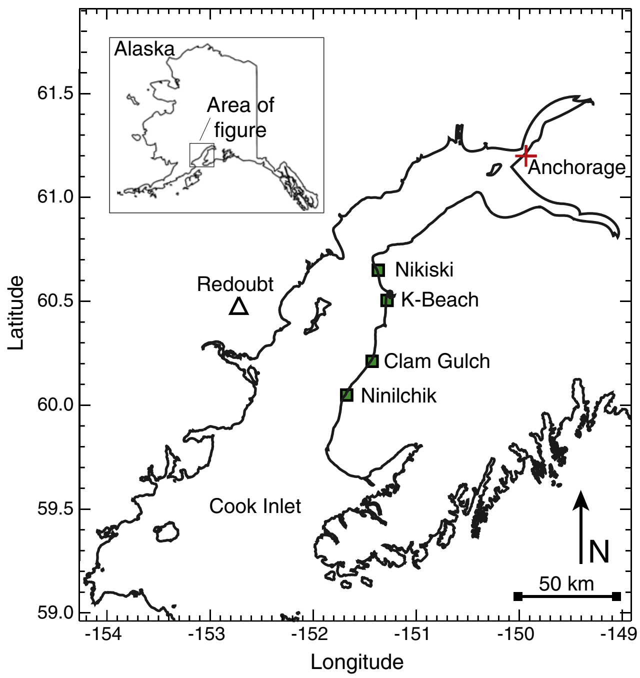

Fig. 1. Map of the locations of the lightning mapping stations (squares) and Redoubt Volcano (triangle).

as a VEI 3 event (Schaefer, 2011). A 4-station LMA was deployed on the east side of Cook Inlet about two months before the eruption to study the electrical activity of the volcano. During the two week period of explosive activity, the ash plumes from Redoubt Volcano produced prolific lightning, which was recorded by the LMA, though visual observations were scarce due to inclement weather in the area.

The research presented in this article expands on the Augustine Volcano results and shows the relationship between the eruptive and electrical activity at Redoubt Volcano in an effort to understand what lightning can tell us about a volcanic eruption. We present an overview of the electrical activity that occurred during the eruptive events and compare it to the previous observations from Augustine Volcano. The trends observed in the progression of flash rate and flash area over time are shown and the types of lightning discharges that occurred throughout the eruption column are discussed. Finally, the electrical activity is compared to the peak plume heights and the seismic and acoustic signals from each explosive event.

2. Data and methods

This study used lightning data from the New Mexico Tech Lightning Mapping Array, seismic, acoustic, and radar data from the Alaska Volcano Observatory, and measurements of cloud-to-ground lightning from the Alaska BLM and the World Wide Lightning Location Network.

2.1. The Lightning Mapping Array

Four LMA stations were installed on the Kenai Peninsula, approximately 80 km east of Redoubt Volcano, between 28 and 31 January 2009. Station sites were selected based on access to AC power and broadband internet, on having a line-of-sight view to Redoubt Volcano, and on being a radio frequency (RF) quiet location. The internet, line of sight, and noise constraints greatly limited the number of desirable sites, so the authors made use of the best locations available. A map of the station locations is shown in Fig. 1. Although each station had a line-of-sight view to Redoubt Volcano, the actual vent of the volcano was blocked from view at the stations because there was a ridge on the eastern side of the volcano that extended approximately 600 m above the vent. This prevented any electrical signals that occurred below and behind the ridge from reaching the stations.

The LMA uses time-of-arrival methods (Rison et al., 1999) to locate sources of VHF radiation (typically 63 MHz; in this deployment 63 and 57 MHz were used) that are produced during the development of lightning channels. In successive short time windows (10 or 80 μs, depending on the operating mode), the peak amplitude and arrival time of the received power is recorded if the signal exceeds a local noise threshold. The LMA was operating in 10 μs mode during the Redoubt Volcano deployment. Each station uses timing from a GPS receiver to measure the arrival times with an accuracy of 40–50 ns. Each electrical signal recorded by the LMA represents a small piece of a discharge, and hundreds or thousands of signals may be recorded for one lightning discharge, depending on the size of a discharge. A minimum of four stations is needed to determine the three dimensional location and time of the source event.

An example of the data recorded by an LMA station is shown in Fig. 2. In each of these three plots, the colors indicate the relative density of points, purple being least dense and red most dense. Panel (a) shows the peak power received in each 10 μs time window. The bands of background radiation (the steady purple sources between roughly −80 and −70 dBm and the greenish sources below −80 dBm) throughout the plot are caused by local noise sources such as electronics, motors, or transformers. A discrete vertical line on a plot of this time scale is most likely caused by a lightning discharge, but can also be produced by a strong, discrete noise source. Panel (b) shows how often the signal was above the power threshold in each time window (referred to as the number of points above threshold), and the time between each recorded signal is shown in panel (c). The maximum value for the number of points above threshold depends on the size of the time window that each signal is recorded in. If the time window is 10 μs, the maximum is 250 and if the time window is 80 μs, the maximum is 2000.

To accurately locate the three dimensional position of a lightning source, the LMA stations must be sufficiently separated from each other so that the signal from a source arrives at each station at significantly different times (Thomas et al., 2004). The four stations, Nikiski, K-Beach, Clam Gulch and Ninilchik, were all approximately equidistant from Redoubt Volcano due to the limitations on available station sites, with distances ranging from 77 to 81 km. In this situation, variations in the altitude of a source would not result in a large enough change in the arrival time differences between pairs of stations. For example, the difference in arrival time between the Clam Gulch and K-Beach stations will be nearly the same for a source located 5 km above Redoubt Volcano as for one 10 km above, making it impossible to determine the altitude of the source. Due to this limitation, the x (east–west) and y (north–south) positions of the sources were determined assuming a fixed altitude of 5 km. Fig. 3 shows the predicted absolute errors in the x and y locations for test data at 5 km altitude using 40 ns timing noise in the test data. The errors were determined from the covariance matrix resulting from solving the non-linear system of equations describing the arrival time of a source for the parameters x, y, and t (time) assuming a fixed z (Thomas et al., 2004). The errors in the x and y position were less than 200 m within a 50 km radius of Redoubt Volcano.

Some of the located data were processed using only the arrival times from 3 stations because there were only 3 stations operating during these particular times due to unexpected power issues. The rest of the locations were determined using arrival times from all 4 stations. This difference is noted throughout the article where pertinent.

2.2. Cloud-to-ground lightning

Locations and times of cloud-to-ground lightning were obtained from the World Wide Lightning Location Network (WWLLN)