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Eruption mass estimation using infrasound waveform inversion and ash and gas measurements: Evaluation at Sakurajima Volcano, Japan

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A B S T R A C T

Eruption mass and mass flow rate are critical parameters for determining the aerial extent and hazard of volcanic emissions. Infrasound waveform inversion is a promising technique to quantify volcanic emissions. Although topography may substantially alter the infrasound waveform as it propagates, advances in wave propagation modeling and station coverage permit robust inversion of infrasound data from volcanic explosions. The inversion can estimate eruption mass flow rate and total eruption mass if the flow density is known. However, infrasound-based eruption flow rates and mass estimates have yet to be validated against independent measurements, and numerical modeling has only recently been applied to the inversion technique. Here we present a robust full-waveform acoustic inversion method, and use it to calculate eruption flow rates and masses from 49 explosions from Sakurajima Volcano, Japan. Six infrasound stations deployed from 12–20 February 2015 recorded the explosions. We compute numerical Green's functions using 3-D Finite Difference Time Domain modeling and a high-resolution digital elevation model. The inversion, assuming a simple acoustic monopole source, provides realistic eruption masses and excellent fit to the data for the majority of the explosions. The inversion results are compared to independent eruption masses derived from ground-based ash collection and volcanic gas measurements. Assuming realistic flow densities, our infrasound-derived eruption masses for ash-rich eruptions compare favorably to the ground-based estimates, with agreement ranging from within a factor of two to one order of magnitude. Uncertainties in the time-dependent flow density and acoustic propagation likely contribute to the mismatch between the methods. Our results suggest that realistic and accurate infrasound-based eruption mass and mass flow rate estimates can be computed using the method employed here. If accurate volcanic flow parameters are known, application of this technique could be broadly applied to enable near real-time calculation of eruption mass flow rates and total masses. These critical input parameters for volcanic eruption modeling and monitoring are not currently available.

1. Introduction

Quantification of the amount, relative proportions, and location of volcanic emissions, including both tephra and gas, is critical for mitigating eruption hazards and understanding eruption dynamics. However, real-time, continuous volcanic emissions measurements are difficult to obtain. Numerous factors such as cloud cover, estimation of wind velocity, radiation intensity, instrument limitations, and variable volcanic activity make obtaining remotely-sensed measurements of volcanic emissions difficult, particularly in remote and/or frequently cloudy regions (e.g. Kern et al., 2010; Lopez et al., 2013a; Williams-Jones, 2008). Geophysical signals can provide information on eruption dynamics and volcanic emissions. Infrasound, or low frequency sound waves (below ~20 Hz), has become an increasingly common and effective tool to monitor and study volcanic eruptions (e.g. Fee and Matoza, 2013;

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Johnson and Ripepe, 2011). Relating infrasound to volcanic emissions shows particular promise (e.g. Dabrowa et al., 2011; Fee et al., 2017; Lopez et al., 2013b), suggesting that infrasound may provide a tool to indirectly quantify and characterize volcanic emissions in near real-time.

Adequate characterization of infrasonic wave propagation from the explosive source to the receiver is critical for accurate infrasound-based constraints on explosion parameters, including eruption location, size, and duration. Topography and atmospheric structure may substantially affect the acoustic wave as it propagates, leading to large errors in estimated explosive source parameters if not addressed. Recent advances in numerical modeling have provided a means to accurately model the acoustic wave propagation around volcanoes in an efficient manner (e.g. Kim and Lees, 2014; Lacanna and Ripepe, 2012). Building on methods developed in volcano seismology (e.g. Chouet and Matoza, 2013; Ohminato et al., 1998), Kim et al. (2015) presented a waveform inversion technique that uses infrasound data to estimate the volume flux from volcanic eruptions using 3-D numerical Green's functions computed by Finite Difference Time Domain (FDTD) modeling. Previous acoustic inversion studies (e.g. Johnson et al., 2008; Johnson and Miller, 2014; Kim et al., 2012) relied on 1-D Green's functions that have been shown to be invalid in the presence of crater morphology and complex topography typical of volcanoes (Kim et al., 2015).

Although promising, volcanic eruption volume and mass estimates derived from infrasound have not been tested extensively or validated using independent observations, particularly for ash-rich eruptions. Firstov and Kravchenko (1996) introduced a technique to estimate the gas volume of a volcanic explosion assuming a monopole acoustic source. This technique was then applied at multiple other volcanoes. For example, Johnson et al. (2008, 2004) used data from Erebus Volcano, Antarctica to invert for the source volume flux and estimated the relative monopole contribution to the source. Dalton et al. (2010) compared infrasound-derived gas volumes from Pacaya Volcano, Guatemala with those from an ultraviolet camera, and found an order of magnitude agreement. Albert et al. (2015) examined gas slug burst events from Tolbachik Volcano, Kamchatka and compared infrasound-derived gas volume estimates with those gleaned from satellites, also finding general agreement. Recently, Delle Donne et al. (2016) used multiple acoustic-based methods to determine the gas flux from explosions at Stromboli Volcano, Italy. These estimates generally compared favorably with independently derived gas flux from a UV camera, but still show a substantial range of values. De Angelis et al. (2016) applied the infrasound waveform inversion technique to explosions at Santiaguito Volcano, Guatemala and integrated thermal infrared imagery to examine eruption and plume dynamics. However, none of these studies incorporated numerical Green's functions and effects of topography, which are known to significantly affect flux (and other source) estimates (Kim et al., 2015). Additionally, these studies focused on gas-rich, ash-poor eruptions. Ash may change the infrasound source mechanism and will affect the volcanic jet density, which are both important factors in the inversion. Ash-rich eruptions also pose the greatest hazard to local populations and air traffic, and constraining the volume and mass flux (or flow rate) from these eruptions, potentially in real-time, would contribute significantly to risk mitigation in volcanic regions.

In this manuscript we build upon the infrasound waveform inversion technique of Kim et al. (2015) that incorporates numerical Green's functions and work towards robust, quantitative estimates of eruption parameters using infrasound. We apply this method to compute volumetric flow rate and total eruption volume for 49 explosions from Sakurajima Volcano. We convert these volume estimates to masses using estimates of bulk flow density from similar eruptions. We attempt to validate the infrasound-derived eruption masses by comparing them to independently derived, ground-based eruption mass estimates constrained through ash sampling and remotely sensed measurements of SO_2 emission rates. In general, the infrasound and ground-based eruption masses are similar (to within less than an order of magnitude), suggesting promise for using infrasound data to accurately constrain volcanic emissions from explosive eruptions.

2. Data collection

A multiparameter dataset was collected at Sakurajima Volcano, Japan between 12–20 February 2015 (Fig. 1). Six Hyperion IFS-5200 digital infrasound sensors were deployed at ranges of 2.1–6.5 km from the active Showa Crater (Fig. 1A). The six stations encircled the volcano and provided good azimuthal coverage. The sensors recorded data at 250 Hz and have a flat frequency response between 0.02–250 Hz. The sensitivity is 4.92 mV/Pa and the linear pressure response is $\pm$1000 Pa.

We collected volcanic ash using ash traps deployed at 10 sites on the southeastern flank of the volcano, downwind of Showa Crater (Fig. 1A). The sampling sites were located in wind-protected areas to minimize sample contamination by resuspended ash, yet easily assessable by road, which allowed prompt sample retrieval between eruptions. We used stainless steel bowls and aluminum trays with sampling areas of 0.102 m^2 and 0.144 m^2, respectively, as ash traps. This size was sufficient for collecting representative amounts of ash and portable enough for transporting in a vehicle to our sample processing facility. Five ash sample sets were collected for individual explosive events, i.e. ash traps were deployed immediately before the onset of an individual explosion and retrieved at the end of ashfall produced by that event. In addition, we collected three multiple-event sample sets, which include ash from four to eleven individual explosions.

SO_2 emission rates were calculated from remote measurements of Sakurajima's plume using a FLYSPEC ultraviolet (UV) spectrometer system (Horton et al., 2006). This method uses the absorption of UV radiation by SO_2 gas to quantify the amount of SO_2 within an atmospheric column following DOAS principles (Platt and Stutz, 2008). Continuous measurements of SO_2 column density (molecules/cm^2) across Sakurajima's plume were collected in scanning mode 3.6 km to the east of the vent from site KUR (Fig. 1A) (31.5835°N, 130.7016°E) during daylight hours on 13, 14 and 17 February 2015 and in traverse mode by driving underneath the plume on 15 February 2015. These SO_2 column density measurements were integrated across the plume width (calculated geometrically in scanning mode and using GPS location in traverse mode) and multiplied by the average wind speed (a proxy for plume speed) provided for Sakurajima on 2-h intervals by the Japan Meteorological Agency, to calculate SO_2 emission rates (t/d or kg/s). Visual observations were also made at station KUR. A photo of a typical large explosion observed during the study period (Event 35) is shown in Fig. 1B.

3. Methods

Here we describe the methods employed to separately derive eruption volumes and masses from Sakurajima explosions using: (1) infrasound waveform inversion, and (2) a combination of ground-based ash sampling and remote sensing of SO_2 gas. The ObsPy Python seismic toolbox (Beyreuther et al., 2010) is used to analyze the infrasound data, and the explosions are identified with the toolbox's network coincidence trigger using the following procedure. After removing travel time from the station to source, we apply the STA/LTA method with window lengths of 1/20 s, respectively, and a threshold of 10 on data filtered between 0.3–20 Hz