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Ash-plume dynamics and eruption source parameters by infrasound and thermal imagery: The 2010 Eyjafjallajökull eruption

M. Ripepe [a,*], C. Bonadonna [b], A. Folch [c], D. Delle Donne [a], G. Lacanna [a], E. Marchetti [a], A. Höskuldsson [d]

[a] Department of Earth Sciences, University of Florence, via LaPira, 4, 50121 Firenze, Italy
[b] Earth and Environmental Sciences Section, University of Geneva, Geneva, Switzerland
[c] Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS), Barcelona, Spain
[d] Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

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ABSTRACT

During operational ash-cloud forecasting, prediction of ash concentration and total erupted mass directly depends on the determination of mass eruption rate (MER), which is typically inferred from plume height. Uncertainties for plume heights are large, especially for bent-over plumes in which the ascent dynamics are strongly affected by the surrounding wind field. Here we show how uncertainties can be reduced if MER is derived directly from geophysical observations of source dynamics. The combination of infrasound measurements and thermal camera imagery allows for the infrasonic type of source to be constrained (a dipole in this case) and for the plume exit velocity to be calculated (54–142 m/s) based on the acoustic signal recorded during the 2010 Eyjafjallajökull eruption from 4 to 21 May. Exit velocities are converted into MER using additional information on vent diameter (50 ± 10 m) and mixture density (5.4 ± 1.1 kg/m^3), resulting in an average $\sim 9 \times 10^5$ kg/s MER during the considered period of the eruption. We validate our acoustic-derived MER by using independent measurements of plume heights (Icelandic Meteorological Office radar observations). Acoustically derived MER are converted into plume heights using field-based relationships and a 1D radially averaged buoyant plume theory model using a reconstructed total grain size distribution. We conclude that the use of infrasonic monitoring may lead to important understanding of the plume dynamics and allows for real-time determination of eruption source parameters. This could improve substantially the forecasting of volcano-related hazards, with important implications for civil aviation safety.

1. Introduction

Real-time forecasting of ash dispersal strongly depends on the characterization of Eruption Source Parameters (ESP), such as plume height, Mass Eruption Rate (MER), and Total Grain Size Distribution (TGSD), which are often difficult to be provided with the necessary accuracy within the first hours of an eruption (Mastin et al., 2009). If the definition of no-fly zones based on ash concentration thresholds consolidates as an International Civil Aviation Organization (ICAO) standard product, operational ash cloud forecasting will require more precise quantifications of the ESP, and, in particular, of the MER. The 2010 Eyjafjallajökull summit eruption revealed deficiencies in the current ash cloud forecasting system (mainly assessment of model input parameters and definition of safe ash concentration thresholds), which was proved to have serious implications on the air-travel infrastructure (Miller, 2011; Ulfarsson and Unger, 2011; O'Regan, 2011). This ash-rich explosive eruption was characterized by nearly continuous injection of tephra into the atmosphere associated with long-lasting bent-over plumes, mostly dispersed toward east and southeast, reaching an average height of about 4 km with peaks of 8 km a.s.l. (Arason et al., 2011). Bent-over plumes (i.e. weak plumes) develop when the velocity of the surrounding wind is higher than the plume exit velocity. This is in contrast to strong plumes, characterized by an ascending velocity of the buoyant column larger than that of wind. Weak plumes are significantly more frequent and, when associated with long-lasting eruptions, can not only affect local communities but also cause prolonged disruptions in the global air traffic, with effects that go far beyond the direct impacts on the air transport industries (Ernst et al., 1994; Guffanti et al., 2010; Miller and Casadevall, 2000; Prata and Tupper, 2009; Rose et al., 1995; Scollo et al., 2009; O'Regan, 2011).Strong and weak plumes are characterized by significantly different dynamics (e.g., Morton et al., 1956; Briggs, 1969; Turner, 1973; Wright et al., 1984; Sparks, 1986; Carey and Sparks, 1986; Coelho and Hunt, 1989; Bursik,

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* Corresponding author. Tel.: +39 055 275 7479; fax: +39 055 218 628.
E-mail address: maurizio.ripepe@unifi.it (M. Ripepe).

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2001) and result in very different tephra deposits (*e.g.*, Ernst et al., 1994, Bonadonna et al., 2005). As a result, empirical and theoretical relations that link plume height and MER for strong plumes (*e.g.*, Wilson and Walker, 1987; Sparks, 1986; Mastin et al., 2009) cannot be easily extrapolated to weak plumes, making the real-time characterization of the source term even more complex (Degruyter and Bonadonna, 2012). In this case, geophysical monitoring of vent processes can provide an alternative characterization of the source term based on plume dynamics at the vent.

Volcanic eruptions are generally associated to strong-amplitude seismic tremors caused by the migration of magma through volcanic conduits, and/or by the dynamics of gas decoupled from the liquid magma (Nishimura, 1995). Detailed analyses of reduced displacements of eruption tremors at several volcanoes have revealed a linear relation between the reduced displacement of tremor and the Volcanic Explosivity Index (McNutt, 2004). However, a simple procedure to deduce general scaling relationships to estimate plume height directly from seismic signals does not exist yet (Nishimura and McNutt, 2008; Prejean and Brodsky, 2011). Tremors can actually be associated to magma intruding within the volcanic body as well as to oscillations of the magma column during the eruption. This multiplicity of tremor sources complicates the use of tremor signals as a proxy for eruption intensity (Caplan-Auerbach and McNutt, 2003). In fact, the 2010 Eyjafjallajökull eruption highlighted this difficulty since tremor amplitudes reached the highest values during the low-discharge effusive phase, from 18 April to 4 May (Sigmundsson et al., 2010; Gudmundsson et al., 2012).

In addition to seismicity, volcanic activity generates infrasonic waves (acoustic waves below 20 Hz), which efficiently propagate in the atmosphere allowing the remote monitoring of volcanic activity in large areas (*e.g.* Matoza et al., 2011a).

Infrasound associated with explosive eruptions is generally produced by the rapid expansion of the gas–particle mixture within the conduit and, in consequence, is related to the dynamics of the volume outflow and thus to the intensity of the eruption.

Unlike seismology, infrasound is, thus, intimately linked to the magma fragmentation process and, in general, to any other phenomenon well coupled with the atmosphere (any source inducing a volume change in the atmosphere is a potential producer of infrasonic waves). For this reason, in the last decades, volcano acoustics is slowly becoming a reality in monitoring procedures also at a local scale (see Johnson and Ripepe, 2011, for a review).

The CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organisation) International Monitoring System (IMS) infrasonic network (Campus and Christie, 2010) operating since early 2000 has shown how efficient the modern infrasound technology is in detecting small pressure perturbation (<0.01 Pa) generated by moderate (VEI >2) volcanic activity (*e.g.* Le Pichon et al., 2005) also at large distances up to 9000 km (Dabrowa et al., 2011). The ash-plume activity of the volcano Ejyafjallajokull in Iceland was detected by the IMS stations in Europe, Russia and North Africa up to a distance of 3600 km (Matoza et al., 2011b). From the sole monitoring point of view, during a volcanic eruption, infrasound provides information on the location of the source processes and intensity of the eruption, and gives direct and rapid evidence on the variations of the explosive activity.

In this paper we discuss the real-time evaluation of MER and plume height using infrasonic array at local distance (<10 km). We analyze the potential of this methodology as a reliable alternative for a better characterization of relevant ESP, especially for eruptions associated with weak plumes, such as those produced during the Eyjafjallajökull 2010 eruption.

First we summarize the characteristics of the infrasonic monitoring (Section 2) and the thermal camera (Section 3) deployed at Eyjafjallajökull during 4–21 May, 2010. Section 4 discusses how ESP can be estimated by acoustic pressure. An indirect validation of the methodology, comparing radar plume height measurements with heights calculated from the acoustic-derived MER, is presented in Section 5. Finally, we conclude with a discussion on the implications for real-time evaluation of ESP.

2. Infrasonic monitoring at Eyjafjallajökull

We recorded the ash plume activity of Eyjafjallajökull using a 4-element infrasonic array with a triangular geometry and an aperture (maximum distance between two elements) of ~120 m (EJA in Fig. 1A and B). The array was installed in Thorvaldseyri, south of Eyjafjallajökull, at a distance of ~8.3 km from the craters. Each array element was equipped with differential pressure transducer with a sensitivity of 25 mV/Pa in the frequency band 0.001–50 Hz and a noise level of 10^{-2} Pa (Marchetti et al., 2009). These sensors were chosen for their wide frequency band, good pressure sensitivity, and low power requirement (~60 mW). All the array elements were connected to the central station and acoustic data were digitized using a 24 bits Guralp CMG-DM24 at the sampling rate of 100 Hz, and recorded both on site and transmitted via Internet link to the Icelandic Meteorological Office (IMO). Time synchronization was achieved with a GPS receiver. A second acoustic station (YHL in Fig. 1A) equipped with the same differential pressure transducer and acquisition system was temporally deployed eastward of the crater at a distance of ~10.6 km.

Location of the infrasonic source is performed by array multichannel semblance analysis applied on a grid-searching procedure (Ripepe and Marchetti, 2002) to identify signals from noise in terms of propagation back-azimuth and apparent velocity. For a 120 m aperture array the expected azimuth resolution is $<2^\circ$ (Ulivieri et al., 2011), which corresponds to ~250 m at a slant distance of 8300 m.

The array data processing shows that most of the acoustic activity came from a back-azimuth direction of ~5°N, consistent with the position of the erupting crater during the last phase of the Eyjafjallajökull eruption (Fig. 2). The peak excess pressure of the signals associated with this back-azimuth shows how the activity at the crater was quite high during the first week of May

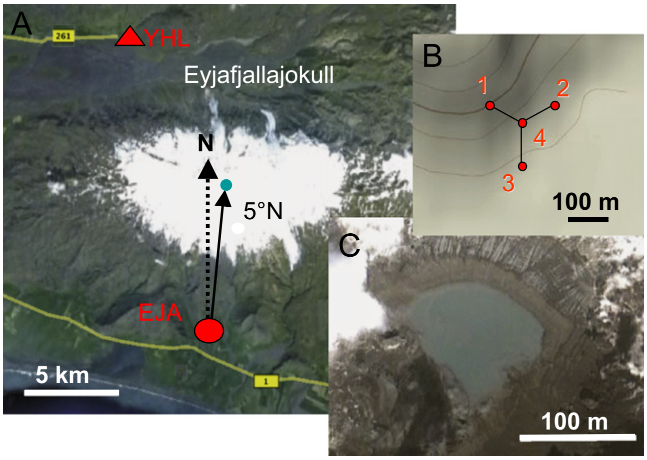

Fig. 1. (A) Map with the position of the array EJA and the acoustic station YHL. The array (B) has a triangle geometry with an aperture of 120 m and a distance of ~8.3 km from the crater. (C) Satellite image of the lake formed in 2011 inside the active crater which has a diameter of ~70 m and is oriented at 5°N from the array.