Journal of Volcanology and Geothermal Research 300 (2015) 129–147

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Volcanic plume vent conditions retrieved from infrared images: A forward and inverse modeling approach

Matteo Cerminara [a,b,*], Tomaso Esposti Ongaro [b], Sébastien Valade [c], Andrew J.L. Harris [d]

[a] Scuola Normale Superiore di Pisa, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy
[c] University of Florence, Department of Earth Sciences, Italy
[d] Université Blaise Pascal, Laboratoire Magmas et Volcans, Clermont-Ferrand, France

ARTICLE INFO

Article history:
Received 5 May 2014
Accepted 22 December 2014
Available online 5 January 2015

Keywords:
Volcanic ash plume
Infrared imaging
Thermal camera
Inversion
Mass flow
Particle size

ABSTRACT

We present a coupled fluid-dynamic and electromagnetic model for volcanic ash plumes. In a forward approach, the model is able to simulate the plume dynamics from prescribed input flow conditions and generate the corresponding synthetic thermal infrared (TIR) image, allowing a comparison with field-based observations. An inversion procedure is then developed to retrieve vent conditions from TIR images, and to independently estimate the mass eruption rate.

The adopted fluid-dynamic model is based on a one-dimensional, stationary description of a self-similar turbulent plume, for which an asymptotic analytical solution is obtained. The electromagnetic emission/absorption model is based on Schwarzschild's equation and on Mie's theory for disperse particles, and we assume that particles are coarser than the radiation wavelength (about 10 μm) and that scattering is negligible. In the inversion procedure, model parameter space is sampled to find the optimal set of input conditions which minimizes the difference between the experimental and the synthetic image.

Application of the inversion procedure to an ash plume at Santiaguito (Santa Maria volcano, Guatemala) has allowed us to retrieve the main plume input parameters, namely mass flow rate, initial radius, velocity, temperature, gas mass ratio, entrainment coefficient and their related uncertainty. Moreover, by coupling with the electromagnetic model we have been able to obtain a reliable estimate of the equivalent Sauter diameter of the total particle size distribution.

The presented method is general and, in principle, can be applied to the spatial distribution of particle concentration and temperature obtained by any fluid-dynamic model, either integral or multidimensional, stationary or time-dependent, single or multiphase. The method discussed here is fast and robust, thus indicating potential for applications to real-time estimation of ash mass flux and particle size distribution, which is crucial for model-based forecasts of the volcanic ash dispersal process.

1. Introduction

Volcanic plumes are produced during explosive eruptions by the injection of a high-temperature gas–particle mixture into the atmosphere. Their dynamics are controlled by several factors (including vent overpressure, crater shape, wind) but, following Morton et al. (1956) and Wilson (1976), it has been recognized that mass flow rate (or eruption intensity) and mixture temperature mainly control the final plume height in stratified environments. More precisely, plume maximum height $H_{\max}$ depends strongly on the steady rate of release of thermal energy in watts at the crater $\dot{Q}$ (Wilson et al., 1978). In particular, the following empirical formula has been widely used in volcanology: $H_{max} \propto \dot{Q}^{1/4}$ (e.g., Mastin et al., 2009). In convective regimes and for the most intense eruptions, volcanic plumes are able to reach stratospheric layers, where ash can persist for years and affect climate, mesoscale circulation, air quality and endanger aviation transport (e.g., Guffanti and Tupper, 2014). Due to their associated fallout, even weak volcanic plumes can have large impacts on populations living close to the volcano, especially in highly urbanized regions around active volcanoes (e.g., Thomas et al., 2014).

Despite the advancement of physical models describing eruption conditions and the subsequent atmospheric dispersal of the gas–particle mixture during an explosive eruption, one of the main obstacles to the full understanding of volcanic plume dynamics is the difficulty in obtaining measurements of the ascent dynamics and plume properties. Indeed, not only are measurements difficult and dangerous, but

* Corresponding author at: Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via della Faggiola 32, 56126 Pisa, Italy. Tel.: +39 03381272966.
E-mail address: matteo.cerminara@gmail.com (M. Cerminara).

http://dx.doi.org/10.1016/j.jvolgeores.2014.12.015
0377-0273/

repeatability is an issue: eruptions differ from each other (even at the same volcano) and are too infrequent to allow for construction of a statistically robust data set (Deligne et al., 2010). While this is certainly true for large eruptions (exceeding 0.1 km^3 of total erupted mass, or a Volcanic Explosive Index – VEI > 3 – Newhall and Self, 1982), persistent but low intensity explosive activity is common at several volcanoes such as Stromboli (Giberti et al., 1992; Harris and Ripepe, 2007) Santa Maria (Bluth and Rose, 2004; Johnson et al., 2004; Sahetapy-Engel and Harris, 2009a) and Soufrière Hills (Clarke et al., 2002; Druitt and Kokelaar, 2002). Such systems offer natural laboratories where methodologies and models for application to rarer, but more energetic events, can be prepared and tested. However, even in such cases, direct measurement of syneruptive conditions is extremely difficult, so that volcanologists must rely on indirect (remote sensing) measurement techniques.

Our current understanding of volcanic plume dynamics is largely based on visual observations, field observation (e.g. evolution of the thickness of the deposits around the vent) and on one-dimensional plume models. There is a general consensus that the fundamental mechanism driving the ascent of volcanic plumes is the conversion of its thermal energy into kinetic energy through the quasi-adiabatic expansion of hot volcanic gases and atmospheric air entrained by turbulence (Sparks et al., 1997). One-dimensional models translating this concept into mathematical language (Wilson, 1976; Woods, 1988; Kaminski et al., 2005) have played a key role in advancing our understanding of the physics of volcanic plumes. One of the reasons behind their success is also that simple models rely on simple measurements for validation, allowing for solution with a limited number of parameters. In the case of eruption plume models, one observable is sufficient, namely the plume height. This can be measured using photogrammetry, infrared imaging, satellite remote sensing, ceilometers, radio and radio-acoustic sounding (e.g., Tupper et al., 2003). Only one adjustable parameter is then needed to fit plume observations, namely a self-similarity coefficient or the entrainment coefficient. This linearly correlates the rate of air entrainment to the average vertical plume velocity (Taylor, 1945; Morton et al., 1956).

On the contrary, the plume interior is generally invisible to the observer, and there is no way to measure mixture density from simple visual observation. As a result, imaging techniques (here defined as the process by which it is possible to observe the internal part of an object which cannot be seen from the exterior) at different wavelengths are needed to obtain data regarding the plume interior (Scollo et al., 2012).

Thermal infrared cameras have become affordable in the last 15 years and their use in volcanic plume monitoring has become popular (Spampinato et al., 2011; Ramsey and Harris, 2013; Harris, 2013). To date they have been used to classify and measure bulk plume properties, such as plume front ascent rates, spreading rates and air entrainment rates for both gas, ash and ballistic rich emissions (Harris and Ripepe, 2007; Patrick et al., 2007; Sahetapy-Engel and Harris, 2009a; Webb et al., 2014), analysis of particle launch velocities, size distributions and gas densities (Delle Donne and Ripepe, 2012; Harris et al., 2012) and particle tracking velocimetry (Bombrun et al., 2013). Recent deployments have involved the use of two thermal cameras: one close up to capture the at-vent dynamics as the mixture exits from the conduit and one standing off to obtain full ascent dynamics as the plume ascends to its full extent. Recently, Valade et al. (2014) have developed a procedure to extract from thermal infrared (TIR) images an estimate of the entrainment coefficient and other plume properties including plume bulk density, mass, mass flux and ascent velocity.

However, recovery of the plume ash mass content and grain size distribution in near-real time remains a major challenge. Experiments and modeling by Prata and Bernardo (2009, 2014) have demonstrated that, under opportune hypotheses (non-opacity of the plume and particle size comparable to the wavelength) thermal cameras can be used for retrieval of ash particle size, mass and optical depth. Such data are crucial for monitoring volcanoes (e.g., Lopez et al., 2013; Webb et al., 2014) and hazard mitigation issues, and especially for the Volcanic Ash Advisory Centers (VAACs) which issue advisories to the aviation community during explosive eruptions. Indeed, VAACs use ash dispersion models (VATD, Volcanic Ash Transport and Dispersion models) to forecast the downstream location, concentration, and fallout of volcanic particles (Stohl et al., 2010). However, to be accurate, such models require quantification of the plume ash concentration and particle size distribution (Mastin et al., 2009; Bonadonna et al., 2012).

In this work we show that recovering this information is possible in a rapid and robust fashion by comparing thermal infrared images that record the emission of a volcanic plume, with synthetic thermal infrared images reconstructed from analytical models.

Our approach inverts time-averaged thermal image data to reconstruct the temperature, ash concentration, velocity profiles and the grain size distribution within the plume. To do this we construct a synthetic thermal image of the volcanic plume starting from the spatial distribution of gas and particles obtained from a fluid dynamic model. The method is based on the definition of the infrared (IR) irradiance for the gas-pyroclast mixture. This is derived from the classic theory of radiative heat transfer (Modest, 2003) with the approximation of negligible scattering (Schwarzschild's equation). The model needs to be calibrated to account for the background atmospheric IR radiation and the material optical properties (Harris, 2013). The absorption and transmission functions needed to compute the irradiance are derived from Mie's theory (Mie, 1908) and can be related, by means of semi-empirical models, to the local particle concentration, grain size distribution and to the optical thickness of the plume. By applying such an IR emission model to the gas–particle distribution obtained from a fluid dynamic model it is possible to compute a synthetic thermal image as a function of the input conditions. We adopt a one-dimensional, time-averaged plume model derived from the Woods (1988) model to simulate the plume profile. The advantage of 1D modeling is that inversion can be performed in a fast and straightforward way by means of minimization of the difference between a synthetic and a measured IR image. However, the method is applicable to any kind of plume model.

In Section 2 we present the IR electromagnetic model (equations and approximations) that we use to produce plume synthetic images. In Section 3 we describe the one-dimensional integral fluid-dynamic model of the plume. In Section 4 we apply the coupled fluid-dynamic-electromagnetic model (forward model) to construct a synthetic thermal image of a volcanic plume. In Section 5 we use this model to invert experimental TIR data acquired during an explosive event at Santiaguito (Santa Maria volcano, Guatemala) to estimate the flow conditions at the vent. Fig. 1 illustrates the methodology and models developed in the paper.

2. Electromagnetic model

Due to the high-temperature of erupted gas and pyroclasts, volcanic plumes emit electromagnetic radiation in the thermal infrared (TIR) wavelengths (8–14 μm). Every single particle radiates as a function of its temperature (through the Planck function) and material properties (each material being characterized by its optical properties (Prata, 1989)). On the other hand, part of the emitted radiation is absorbed by neighboring gas and particles, so that the net transmitted radiation results from the balance between emission and absorption and is a function of the electromagnetic wavelength λ. This balance is expressed by Schwarzschild's equation.

2.1. Schwarzschild's equation

Along an optical path, defined by a curvilinear coordinate s (see Fig. 2), the infinitesimal variation of TIR intensity due to emission at temperature T is proportional to the Planck function

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}}-1}\,, \tag{1}$$