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Combined effects of total grain-size distribution and crosswind on the rise of eruptive volcanic columns

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ABSTRACT

The maximum height of an explosive volcanic column, H, depends on the 1/4th power of the eruptive mass flux, Q, and on the 3/4th power of the stratification of the atmosphere, N. Expressed as scaling laws, this relationship has made H a widely used proxy to estimate Q. Two additional effects are usually included to produce more accurate and robust estimates of Q based on H: particle sedimentation from the volcanic column, which depends on the total grain-size distribution (TGSD) and the atmospheric crosswind. Both coarse TGSD and strong crosswind have been shown to decrease strongly the maximum column height, and TGSD, which also controls the effective gas content in the column, influences the stability of the column. However, the impact of TGSD and of crosswind on the dynamics of the volcanic column are commonly considered independently. We propose here a steady-state 1D model of an explosive volcanic column rising in a windy atmosphere that explicitly accounts for particle sedimentation and wind together. We consider three typical wind profiles: uniform, linear, and complex, with the same maximum wind velocity of 15 m s^{-1}. Subject to a uniform wind profile, the calculations show that the maximum height of the plume strongly decreases for any TGSD. The effect of TGSD on maximum height is smaller for uniform and complex wind profiles than for a linear profile or without wind. The largest differences of maximum heights arising from different wind profiles are observed for the largest source mass fluxes ($>10^7$ kg s^{-1}) for a given TGSD. Compared to no wind conditions, the field of column collapse is reduced for any wind profile and TGSD at the vent, an effect that is the strongest for small mass fluxes and coarse TGSD. Provided that the maximum plume height and the wind profile are known from real-time observations, the model predicts the mass discharge rate feeding the eruption for a given TGSD. We apply our model to a set of eight historical volcanic eruptions for which all the required information is known. Taking into account the measured wind profile and the actual TGSD at the vent substantially improves (by $\approx$30%) the agreement between the mass discharge rate calculated from the model based on plume height and the field observation of deposit mass divided by eruption duration, relative to a model taking into account TGSD only. This study contributes to the improvement of the characterization of volcanic source term required as input to larger scale models of ash and aerosol dispersion.

1. Introduction

Magmatic gases and ash injected into the atmosphere by explosive volcanic eruptions present a number of potentially severe hazards ranging from fatalities and health problems to major air traffic disruptions (Miller and Casadevall, 2000; Hornwell, 2007; Watson, 2015; Witze, 2015). These hazards are mainly related to the amount of ash injected in the volcanic plume that itself is closely related to the eruptive mass flux and to the total grain-size distribution (TGSD). Field evidence of the TGSD of volcanic particles carried by a Plinian column are provided by ground-based and airborne LIDAR observations (Marenco et al., 2011), satellite measurements (Prata and Prata, 2012; Guéhenneux et al., 2015), direct aircraft sampling (Johnson et al., 2012; Turnbull et al., 2012), and analyses of pyroclastic deposits (Durant and Rose, 2009). Decades of near real-time measurements suggest that the population and concentration of solid fragments vary substantially from the volcanic vent to the maximum plume height during a single eruption. Predicting quantitatively the evolution of the population of particles in the atmosphere is not straightforward although it remains cardinal for the assessment of volcanic hazards related to Plinian eruptions.

The complex behavior of the gas–particle mixture ejected at the volcanic vent stems from the non-linear evolution of the bulk density of the column as it rises and mixes with the atmosphere. Cold atmospheric air is engulfed by turbulent entrainment at the edges of the column and is heated up by the hot solid fragments. If these processes sufficiently reduce the bulk density of the mixture, a positively buoyant plume is formed (Sparks and Wilson, 1976; Woods, 1988). The evolution of the density of the mixture in the column, hence of its dynamics, depends on the relative concentration of air and magma fragments in the flow. The

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concentration of volcanic fragments in the column is progressively reduced at increasing height above the vent by particle sedimentation and by dilution of the volcanic mixture through turbulent entrainment at the edges of the column. The physics of these two processes, and especially their relation to the eruptive mass flux, has to be included in a model of volcanic plume to predict the concentration and flux of ash injected in the volcanic cloud.

To first order, the maximum height of an explosive volcanic column, H (km), depends on the eruptive mass flux, Q (kg s^{-1}), and on the stratification of the atmosphere, N (s^{-1}) (Morton et al., 1956; Settle, 1978). Expressed as scaling laws, the relationship between H, Q, and N has made the observed maximum height H a widely used proxy to estimate the eruptive mass flux (Wilson et al., 1980). However, for more accurate and robust estimates of Q based on H, two additional parameters also need to be taken into account: the TGSD of particles injected into the atmosphere, which controls particle sedimentation and the fraction of magmatic gas released at fragmentation (Girault et al., 2014), and the strength of the atmospheric wind (Bursik, 2001). Previous studies have made significant progress in identifying the key parameters governing turbulent entrainment in a volcanic column (e.g., Woods, 1988; Kaminski et al., 2005; Ogden et al., 2008; Suzuki and Koyaguchi, 2010) and particle sedimentation from a volcanic column (e.g., Woods and Bursik, 1991; Folch and Felpeto, 2005; Costa et al., 2006, 2010; Barsotti et al., 2008; Girault et al., 2014; Le Roux, 2014; Manzella et al., 2015). A range of observational, theoretical, numerical, and experimental approaches have shown that low-altitude winds tend to enhance turbulent entrainment and to bend the eruptive column, hence reducing its maximum height (e.g., Bursik, 2001; Degruyter and Bonadonna, 2012; Woodhouse et al., 2013; Carazzo et al., 2014; Mastin, 2014). The quantitative influence of this process on the evolution of the TGSD and of ash concentration has not been thoroughly tested yet, and wind effect and particle sedimentation have only been explored independently. In this paper, we propose to fill this gap using a 1D steady-state model of a particle-laden volcanic column rising in a windy atmosphere. This model is built on previous models developed by our group (Carazzo et al., 2008a,b; Girault et al., 2014) and is compared to other 1D and 3D models in the framework of the benchmark exercise (see Costa et al., 2016).

2. A theoretical model of a turbulent volcanic plume in a windy atmosphere

For the sake of completeness, we describe the equations of the model presented in Girault et al. (2014) re-derived to include the effect of a crosswind. The model is set in a Cartesian coordinate system, with z and x denoting the vertical and horizontal distance from the source, respectively. Equations are written using a "Top-Hat" formalism and in a plume-centered coordinate system such as (Hoult et al., 1969; Hewett et al., 1971):

$$\frac{dx}{ds} = \cos\theta, \quad \text{and} \quad \frac{dz}{ds} = \sin\theta, \tag{1}$$

where s is the curvilinear abscissa along the plume axis, and θ is the inclination of the plume centerline relative to the horizontal (Fig. 1).

2.1. Conservation laws

We use the formulation of Woods (1988), subsequently refined by Bursik (2001), for the conservation of mass flux,

$$\frac{d}{ds}\left(\rho U R^2\right) = 2\rho_a R U_e + \sum_{\phi=1}^{N_\phi} \frac{dQ_\phi}{ds} \tag{2}$$

of axial and radial momentum fluxes,

$$\frac{d}{ds}\left(\rho U^2 R^2\right) = (\rho_a - \rho) g R^2 \sin\theta + W \cos\theta \frac{d}{ds}\left(\rho U R^2\right) + U \sum_{\phi=1}^{N_\phi} \frac{dQ_\phi}{ds} \tag{3}$$

$$\left(\rho U^2 R^2\right)\frac{d\theta}{ds} = (\rho_a - \rho) g R^2 \cos\theta - W \sin\theta \frac{d}{ds}\left(\rho U R^2\right) \tag{4}$$

and of thermal energy flux,

$$\frac{d}{ds}\left(\rho c T U R^2\right) = 2\rho_a c_a T_a R U_e - \rho_a g U R^2 \sin\theta + c_p T \sum_{\phi=1}^{N_\phi} \frac{dQ_\phi}{ds} \tag{5}$$

where R is the column radius, U is the average vertical velocity, g is the acceleration of gravity, and πQ_ϕ is the mass flux of ϕ-sized particles characterized by the specific heat c_p. $T_a(z)$, $\rho_a(z)$, and c_a are the temperature, density, and specific heat of the atmosphere, respectively, and T, ρ, and c are those of the bulk mixture. U_e is the "entrainment velocity" at the edge of the plume, and W is the wind speed.

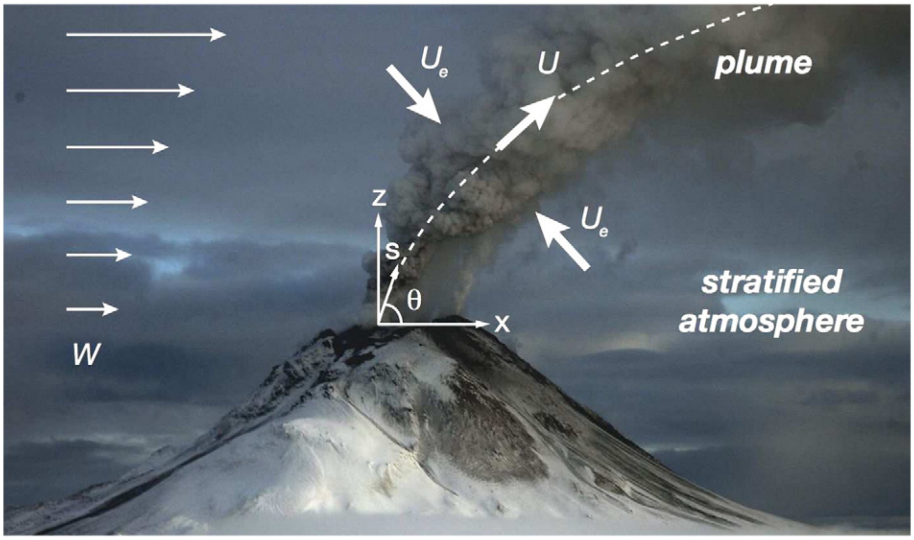

Fig. 1. Photograph of the 2006 Mt. Augustine eruption and coordinate systems used in this study (see text and notation for symbol description).