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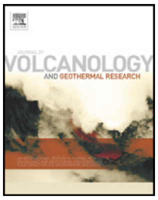

On the relationship between eruption intensity and volcanic plume height: Insights from three-dimensional numerical simulations

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ABSTRACT

Height of plumes generated during explosive volcanic eruptions is commonly used to estimate the associated eruption intensity (i.e., mass eruption rate; MER). In order to quantify the relationship between plume height and MER, we performed a parametric study using a three-dimensional (3D) numerical model of volcanic plumes for different vent sizes. The results of five simulations indicate that the flow pattern in the lower region of the plume systematically changes with vent size, and hence, with MER. For MERs $<4 \times 10^7$ kg s^{-1}, the flow in the lower region has a jet-like structure (the jet-like regime). For MERs $>10^8$ kg s^{-1}, the flow shows a fountain-like structure (the fountain-like regime). The flow pattern of plumes with 4×10^7 kg s^{-1} < MERs $<10^8$ kg s^{-1} shows transitional features between the two flow regimes. Within each of the two flow regimes, the plume height increases as the MER increases, whereas plume heights remain almost constant or even decrease as MER increases in the transitional regime; as a result, the jet-like and fountain-like regimes show distinct relationships of plume height and MER. The different relationships between the two regimes reflect the fact that the efficiency of entrainment of ambient air in the jet-like regime is substantially lower than that in the fountain-like regime. It is suggested that, in order to estimate eruption intensity from the observed plume heights, it is necessary to take the different flow regimes depending on MER into account.

1. Introduction

Explosive eruptions can generate gigantic plumes, called as eruption column or volcanic plume. During such eruptions, a large amount of a mixture of solid pyroclasts (volcanic ash) and volcanic gases are ejected from volcanic vent into the atmosphere. The ejected mixture entrains ambient air and expands because of the heating from the pyroclasts, becoming buoyant and developing an eruption column. As the mixture rises, its density becomes equal to the atmospheric density at the so-called neutral buoyancy level (NBL), because of the atmosphere stratification. Finally, the mixture reaches the top of the column exhausting its momentum and radially spreads around the NBL.

Plume heights such as the total height and NBL are primarily determined by the balance between the thermal energy ejected from the vent and the work done during transport of the ejected material and entrained air through the stratified atmosphere (e.g., Morton et al., 1956; Woods, 1988). Therefore, plume heights increases as the eruption intensity (the mass eruption rate; MER) increases (Woods, 1988). This dependency was obtained from dimensional analyses (Morton et al., 1956) and semi-qualitatively studies based on field observations (Wilson and Walker, 1987; Sparks et al., 1997; Mastin et al., 2009), experimental studies (Carazzo et al., 2008), and numerical studies based on one-dimensional (1D) models of volcanic plume (Woods, 1988; Costa et al., 2016).

The relationships between MER and plume height are commonly derived under the assumptions that the entrainment velocity at the edge of eruption column is approximately proportional to the mean plume velocity along the flow axis at each height and its proportionality coefficient, representing the efficiency of air entrainment, is considered as a constant (e.g., Woods, 1995) or a simple function (Kaminski et al., 2005; Carazzo et al., 2008). On the other hand, a recent study by Suzuki and Koyaguchi (2012) showed that the flow pattern and the efficiency of air entrainment in the lower part of eruption column can fundamentally change depending on the vent size. Their results suggest that these changes affect the dynamics of eruption columns near the vent such as the critical condition for column collapse; however, whether or not these changes near the vent control the plume heights is unclear.

In this study, we carried out a set of numerical simulations of volcanic columns using a 3D fluid dynamic model (e.g., Suzuki et al., 2005; Suzuki and Koyaguchi, 2009, 2013) for different MERs obtained by varying the vent size. We estimated the plume heights from the simulation results and compared the estimated heights with those predicted by a 1D model based on the Buoyant Plume Theory (BPT) which assumes constant efficiency of air entrainment. From the results of 3D simulations and the comparison with those of the 1D model, we evaluated

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the dependency of plume heights on MERs (and the vent sizes). The 3D model used here is somewhat simplified compared with recent more sophisticated models such as ASHEE (Cerminara et al., 2016). The model considers the dilute regime described by Elghobashi (1991) and it used the dusty-gas approximation (i.e., Cerminara et al., 2016). It ignores the effects of pressure disequilibrium at the vent (Carcano et al., 2014) and water condensation (Herzog et al., 1998). In addition, the eddy diffusivity due to subgrid turbulence was not explicitly calculated; the large-eddy simulation was not used. Despite these simplifications, however, the model has successfully reproduced the relationship between MER and plume height obtained by the field observations (Suzuki and Koyaguchi, 2009, 2013).

2. Method and simulation inputs

From the results of numerical simulation, we estimated three characteristic heights of the eruptive plume. The first one is the total (or maximum) eruption column height (H_T). This height is defined as the highest level of an assigned concentration threshold (see Suzuki et al., 2016). Because the total height generally fluctuates with time (e.g., Suzuki and Koyaguchi, 2009), we averaged the results across a specified time window. The second one is the height of the NBL (H_{NBL}), defined as the level where the density difference relative to the atmospheric changes sign from positive to negative. To estimate this height, simulation results were averaged over an appropriate time window and then averaged over the cross-section along the plume axis. The third height is the maximum spreading level H_{MSL}, defined as the height with the maximum radial injection of the erupted material. The H_{MSL} was estimated using horizontally-integrated and temporally averaged profiles of the mass fraction of the erupted material.

We carried out five simulations of eruption plumes with variable vent size, i.e., variable MER. The vent radius, R_0, ranged from 60 m to 267 m; the MER, $\dot{m}_0$, ranged from 2.0×10^7 kg s^{-1} to 4.0×10^8 kg s^{-1}. The other parameters were kept fixed among the simulations. Magmatic temperature and water content were assumed to be 1000 K and 2.84 wt%, respectively, similar to the conditions set for Group H in Suzuki and Koyaguchi (2012). The pressure at the vent is assumed to be in equilibrium with the atmospheric condition. According to the equation of state, the initial density of the ejected material ρ_0 is estimate to be 7.72 kg m^{-3}. The exit velocity w_0 is 230 m s^{-1} corresponding to the Mach number of 2.0, and it is assumed to be constant during eruption. The MER and vent radius is related by an equation of $\dot{m}_0 = \rho_0 \pi R_0^2 w_0$. The common parameters used are listed in Table 1 and the values considered in the different Runs are reported in Table 2. The details of the 3D and 1D models used in this study are described below.

Table 1
Common input parameters and constants for simulations.

Variable	Value
Vent elevation	0 m
Exit velocity	230 m s^{-1}
Exit temperature	1000 K
Exit water fraction	0.0284
Exit density	7.72 kg m^{-3}
Gravity body force	9.81 m s^{-2}
Gas constant of volcanic gas	462 J kg^{-1} K^{-1}
Gas constant of atmospheric air	287 J kg^{-1} K^{-1}
Specific heat of solid pyroclasts	1100 J kg^{-1} K^{-1}
Specific heat of volcanic gas at constant volume	1348 J kg^{-1} K^{-1}
Specific heat of air at constant volume	717 J kg^{-1} K^{-1}
Atmospheric density at 0 km	1.29 kg m^{-3}
Atmospheric temperature at 0 km	273 K
Atmospheric temperature gradient	
0–11 km	−6.5 K km^{-1}
11–20 km	0.0 K km^{-1}
20–32.2 km	1.0 K km^{-1}
32.2–47.4 km	2.8 K km^{-1}

2.1. 3D time-dependent model

In order to investigate how variation of MER due to changes of vent size influences the efficiency of air entrainment and the plume dynamics and heights, we used the pseudo-gas model (Marble, 1970; Suzuki et al., 2005). In the framework of this model, the disequilibrium between the solid pyroclasts and the gas phases is neglected (Cerminara et al., 2016); the mixture of the ejected material (solid pyroclasts and water vapour) and the entrained air is treated as a single fluid whose density is calculated from the mixing ratio of the ejected material and entrained air. This model solves a set of partial differential equations describing the conservation of mass, momentum, and energy, the equation of state, and the equation describing the thermodynamic state of the mixture of pyroclasts, volcanic gas, and air. Details of the numerical procedures used in this study are described in Suzuki et al. (2005) and Suzuki and Koyaguchi (2009).

The simulations were designed to describe the injection of a mixture of pyroclasts and volcanic gas from a circular vent located at 0 km above sea level (a.s.l.) in a windless atmosphere. Mid-latitude atmospheric conditions were taken into account and the profiles of the temperature gradients considered are indicated in Table 1. The atmospheric density and pressure were calculated from the hydrostatic relationship. Free-slip conditions were assumed at the ground boundary, whereas free outflow/inflow conditions were applied at the upper and side boundaries of the computational domain.

Numerical calculations were performed on a generalized coordinate system. The vent diameter consists of 16 grid points. The grid size increases with distance from the vent at a constant rate (by a factor of 1.02) up to the length scale of vent radius. The partial differential equations are solved by the Roe scheme (Roe, 1981) with MUSCL (Monotone Upstream-centred Scheme for Conservation Laws) interpolation (van Leer, 1977) for spatial integration and the time splitting method for time integration.

To obtain a statistically stationary configuration of eruption columns, the 3D simulations were carried out for sufficiently long time. The choice of the critical threshold and time window for averaging were decided a posteriori based on the sensitivity of results (the procedure of the choice is described in Suzuki et al., 2016). The simulated time, and the time window and output interval for averaging are also listed in Table 2. The plume heights obtained from the 3D simulations are denoted by H_T^{3D}, H_{NBL}^{3D}, and H_{MSL}^{3D}.

2.2. 1D steady model

Several sophisticated 1D models of eruption column have been proposed and compared among them by different research groups (Costa et al., 2016). Here we used a simple model with uniform entrainment coefficients proposed by Woods (1988). This model is designed to describe the physical quantities in a steady eruption column as a function of the height above the vent. In this model, the fluxes of mass, momentum, and specific enthalpy along the plume are calculated (Cerminara, 2015). To compare the 1D calculation results with those obtained from the 3D pseudo-gas model, we ignore the disequilibrium effects between solid pyroclasts and gas phases in the 1D model.

From the calculations using the 1D model, we can obtain the total height of eruptive plume (H_T^{1D}) and the height of the NBL (H_{NBL}^{1D}). In the 1D model, the maximum spreading level is practically considered to be same as H_{NBL}^{1D}. We compared H_T^{3D} with H_T^{1D}, and then H_{NBL}^{3D} and H_{MSL}^{3D} with H_{NBL}^{1D}.

3. Simulation results

As we mentioned above, we carried out five Runs with different vent sizes, and hence different MERs. In all 3D simulations describing the time evolution of the eruption plumes, an eruption column and