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Inter-comparison of three-dimensional models of volcanic plumes

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ABSTRACT

We performed an inter-comparison study of three-dimensional models of volcanic plumes. A set of common volcanological input parameters and meteorological conditions were provided for two kinds of eruptions, representing a weak and a strong eruption column. From the different models, we compared the maximum plume height, neutral buoyancy level (where plume density equals that of the atmosphere), and level of maximum radial spreading of the umbrella cloud. We also compared the vertical profiles of eruption column properties, integrated across cross-sections of the plume (integral variables). Although the models use different numerical procedures and treatments of subgrid turbulence and particle dynamics, the inter-comparison shows qualitatively consistent results. In the weak plume case (mass eruption rate 1.5×10^6 kg s^{-1}), the vertical profiles of plume properties (e.g., vertical velocity, temperature) are similar among models, especially in the buoyant plume region. Variability among the simulated maximum heights is ~20%, whereas neutral buoyancy level and level of maximum radial spreading vary by ~10%. Time-averaging of the three-dimensional (3D) flow fields indicates an effective entrainment coefficient around 0.1 in the buoyant plume region, with much lower values in the jet region, which is consistent with findings of small-scale laboratory experiments. On the other hand, the strong plume case (mass eruption rate 1.5×10^9 kg s^{-1}) shows greater variability in the vertical plume profiles predicted by the different models. Our analysis suggests that the unstable flow dynamics in the strong plume enhances differences in the formulation and numerical solution of the models. This is especially evident in the overshooting top of the plume, which extends a significant portion (~1/8) of the maximum plume height. Nonetheless, overall variability in the spreading level and neutral buoyancy level is ~20%, whereas that of maximum height is ~10%. This inter-comparison study has highlighted the different capabilities of 3D volcanic plume models, and identified key features of weak and strong plumes, including the roles of jet stability, entrainment efficiency, and particle non-equilibrium, which deserve future investigation in field, laboratory, and numerical studies.

1. Introduction

Understanding the dynamics of eruption columns during explosive eruptions is one of the central aims of volcanology. In particular, improving the relationships between plume height, vertical distribution of mass, and initial eruptive conditions is crucial to improve forecasts of atmospheric ash dispersal. The maximum height of a volcanic plume is commonly used to estimate its mass eruption rate and vertical distribution of mass (Suzuki, 1983; Sparks et al., 1997; Mastin et al., 2009; Folch, 2012). However, many factors can lead eruption plumes to deviate from these simple empirical relationships (e.g., Tupper et al., 2009). Therefore, it is important to develop a clearer understanding of the behaviour of three-dimensional volcanic plumes under different meteorological and eruptive conditions.

Over the past few decades, a range of numerical models have been developed to examine the dynamics of eruption columns (Costa et al., 2016). In this work we specifically address fluid dynamic models of volcanic plumes which solve the full Eulerian transient mass, momentum, and energy equations for the plume mixture and ambient air in a three-dimensional atmospheric domain. With respect to one-dimensional (1D) integral models discussed in the companion paper (Costa et al., 2016), three-dimensional (3D) models can describe the non-homogeneous features of a volcanic plume, i.e., the time- and space-dependent distribution of the concentration, temperature, pressure, and velocity of each constituent of the eruptive mixture, and the multiphase flow features of the eruptive mixture. In addition, they can explicitly simulate turbulent entrainment of ambient air by resolving the eddy structure of the plume and the stratification and flow circulation in the

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atmosphere. Although 3D models were developed for volcanological applications in the 1990s (Valentine and Wohletz, 1989; Dobran et al., 1993; Oberhuber et al., 1998), only in the last decade 3D simulations have become computationally affordable thanks to the advent of high-performance computing (e.g., Suzuki et al., 2005; Textor et al., 2005; Esposti Ongaro et al., 2008; Herzog and Graf, 2010; Van Eaton et al., 2015; Cerminara et al., 2016a).

In this study, 3D results are used to enhance our understanding of the processes occurring inside volcanic plumes and, in particular, to investigate their non-homogeneous structure. Plume dynamics are mainly analyzed on their time- and space-averaged properties to allow comparison with 1D integral models and discuss their approximations and the capability to capture some features especially relevant for volcanic hazard assessment, such as the maximum plume height and the level of spreading of the umbrella. However, plume average properties are controlled by turbulent fluctuations, occurring on small time and space scales (for a discussion of turbulent scales see, e.g., Cerminara et al., 2016a). These are explicitly resolved in 3D models while they are parameterized in integral models by means of an empirical entrainment coefficient (Morton et al., 1956). Therefore, comparison of 1D and 3D models can allow the improvement the parameterization of entrainment in 1D models (Suzuki and Koyaguchi, 2012; Cerminara et al., 2016b).

This work is a part of a more general inter-comparison study of eruption column models promoted by the IAVCEI Commission on Tephra Hazard Modelling, in which a set of simulations were performed by both 3D models and 1D integral models (Costa et al., 2016). In the present study, we describe the 3D models and discuss their discrepancies and similarities on the basis of the assumptions and approximations made in each modelling approach. Finally, we discuss the method for comparing and analysing 3D simulation results and the implications for modelling volcanic plumes under different meteorological and eruptive conditions.

2. Methods

For this study, 3D numerical simulations were performed with four different models, using the same volcanic and meteorological conditions. Each 3D model is based on the time-dependent solution of the generalized multiphase flow Navier-Stokes equations for conservation of mass, momentum, and energy (or enthalpy), describing the fluid dynamics of the eruptive mixture and the surrounding atmosphere, the thermodynamic equation of state, and the constitutive equations. The key differences between the models are the treatments of the gas-particle mixture, water microphysics and subgrid turbulence. The numerical discretization and solution methods also differ. However, the aim of this inter-comparison (as in Costa et al., 2016) is to compare results with common input parameters, without constraining every aspect of the modelling (e.g., grid resolution, numerical discretization). This approach allows us to evaluate the results of different models as typically employed by the users.

In the following sections, we provide a brief description of each model and the common input parameters used for the inter-comparison. We then describe the specific methods used to quantitatively compare results from 3D models, and then, 1D models.

2.1. Physical formulations

These models describe the injection of a mixture of solid pyroclasts and volcanic gases from a vent into the stratified atmosphere. This inter-comparison study involves four different codes: SK-3D (Suzuki et al., 2005; Suzuki and Koyaguchi, 2009; Suzuki and Koyaguchi, 2013, Suzuki and Koyaguchi, 2015), ATHAM (Active Tracer High-resolution Atmospheric Model; Herzog et al. 2003), ASHEE (Ash Equilibrium Eulerian model; Cerminara et al., 2016a), and PDAC (Pyroclastic Dispersal Analysis Code; Neri et al., 2003; Esposti Ongaro et al., 2007; Carcano et al., 2013). In the present application, SK-3D, ATHAM, and PDAC considered eruption from a circular vent with steady mass flux. In ASHEE, a periodical forcing and a random perturbation of intensity 0.05 U (U being the average flow velocity) has been superimposed to the average inflow to mimic a turbulent inlet at the vent and to trigger fluid instabilities. Such a perturbation has an important role in the jet region, where it significantly anticipates the development of turbulence (Cerminara et al., 2016a,b). The main features of each model are summarized in Table 1 and briefly stated hereafter.

SK-3D employs a pseudo-gas or dusty-gas approximation in which the velocity and temperature are same for all phases (e.g., Marble, 1970). This approximation is also adopted by the 1D models analyzed in the model inter-comparison of Costa et al. (2016), and is physically justified for dilute plumes (volumetric particle concentration < 0.001; Elghobashi, 1991, 1994) containing small particles. Under this approximation, the mixture of solid particles and gas is treated as a single fluid, and particle-gas decoupling is ignored (Suzuki et al., 2005). As a result, SK-3D involves two components: eruptive material (the mixture of solid particles and water vapor) plus dry air.

ATHAM also assumes perfect coupling between particles and the flow in the horizontal direction, but does allow gravitational settling and separation of particles in the vertical direction. ATHAM considers cloud microphysical processes, including the phase changes of water vapor, liquid water, and ice, growth of precipitation (raindrops, hail), and the dynamic effects of latent heat exchange.

ASHEE uses the equilibrium-Eulerian approach (Ferry and Balachandar, 2001), which extends the applicability of the dusty gas model to coarser particles (from $St < 10^{-3}$ to $St < 0.2$, where St is Stokes number; Balachandar and Eaton, 2010; Cerminara et al., 2016a). For volcanic plumes, such a threshold corresponds to ash particles (diameter less than about 1 mm). By using such an approach, the model can describe, to a first order, the kinematic decoupling of particles due to both settling and turbulence.

PDAC can model both the kinetic and thermal non-equilibrium interaction and decoupling between solid particles and gas by adopting an N-phase multicomponent Eulerian description (Neri et al., 2003; Esposti Ongaro et al., 2007; Esposti Ongaro and Cerminara, 2016). In such a description, the gas and particulate phases in the plume can have different velocities and temperatures, because of different injection regimes or because they are subject to different forces (such as the effective gravity, or buoyancy), while drag forces and heat exchange will tend to homogenize the flow.

2.2. Numerical procedures

Numerical procedures also differ among the models. The partial differential equations are solved numerically using a finite difference

Table 1
Summary of the three-dimensional models used in the study. Note that the label numbers 1, 2, 3, and 4 corresponds to 10, 11, 12, and 13 represented in Costa et al. (2016), respectively.

Label	1	2	3	4
Name	ATHAM[a]	SK-3D[b]	ASHEE[c]	PDAC[d]
LES	Yes	No	Yes	Yes
Components	Air, water, particles	Air, erupted material	Air, water, particles	Air, water, particles
Particle fallout	Yes	No	Yes	Yes
Atmospheric moisture	Yes	No	Yes	No
Water latent heat	Yes	No	Yes	No
Cloud microphysics	Yes	No	No	No

[a] Herzog et al. (2003).
[b] Suzuki et al. (2005); Suzuki and Koyaguchi (2009, 2015).
[c] Cerminara et al. (2016a).
[d] Neri et al. (2003); Esposti Ongaro et al. (2007); Carcano et al. (2013).