Journal of Volcanology and Geothermal Research 326 (2016) 2–25

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

# Results of the eruptive column model inter-comparison study

A. Costa [a,b], Y.J. Suzuki [b], M. Cerminara [c], B.J. Devenish [d], T. Esposti Ongaro [c], M. Herzog [e], A.R. Van Eaton [f], L.C. Denby [e], M. Bursik [g], M. de' Michieli Vitturi [c], S. Engwell [c], A. Neri [c], S. Barsotti [c,h], A. Folch [i], G. Macedonio [j], F. Girault [k], G. Carazzo [k], S. Tait [k], E. Kaminski [k], L.G. Mastin [f], M.J. Woodhouse [l], J.C. Phillips [l], A.J. Hogg [m], W. Degruyter [n], C. Bonadonna [o]

[a] *Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy*
[b] *Earthquake Research Institute, The University of Tokyo, Japan*
[c] *Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy*
[d] *Met Office, Exeter, UK*
[e] *Department of Geography, University of Cambridge, UK*
[f] *U.S. Geological Survey, Cascades Volcano Observatory, USA*
[g] *Department of Geology, University at Buffalo, USA*
[h] *Icelandic Meteorological Office, Iceland*
[i] *Barcelona Supercomputing Center, Barcelona, Spain*
[j] *Istituto Nazionale di Geofisica e Vulcanologia, Naples, Italy*
[k] *IPG Paris and Université Paris-Diderot, Paris, France*
[l] *School of Earth Sciences, University of Bristol, UK*
[m] *School of Mathematics, University of Bristol, UK*
[n] *School of Earth and Atmospheric Sciences, Georgia Tech, USA*
[o] *Department of Earth Sciences, University of Geneva, Switzerland*

ARTICLE INFO

*Article history:*
Received 18 September 2015
Accepted 29 January 2016
Available online 6 February 2016

*Keywords:*
Explosive volcanism
Eruptive plumes dynamics
Fluid dynamic models
Model inter-comparison
Eruption source parameters

ABSTRACT

This study compares and evaluates one-dimensional (1D) and three-dimensional (3D) numerical models of volcanic eruption columns in a set of different inter-comparison exercises. The exercises were designed as a blind test in which a set of common input parameters was given for two reference eruptions, representing a strong and a weak eruption column under different meteorological conditions. Comparing the results of the different models allows us to evaluate their capabilities and target areas for future improvement. Despite their different formulations, the 1D and 3D models provide reasonably consistent predictions of some of the key global descriptors of the volcanic plumes. Variability in plume height, estimated from the standard deviation of model predictions, is within ~20% for the weak plume and ~10% for the strong plume. Predictions of neutral buoyancy level are also in reasonably good agreement among the different models, with a standard deviation ranging from 9 to 19% (the latter for the weak plume in a windy atmosphere). Overall, these discrepancies are in the range of observational uncertainty of column height. However, there are important differences amongst models in terms of local properties along the plume axis, particularly for the strong plume. Our analysis suggests that the simplified treatment of entrainment in 1D models is adequate to resolve the general behaviour of the weak plume. However, it is inadequate to capture complex features of the strong plume, such as large vortices, partial column collapse, or gravitational fountaining that strongly enhance entrainment in the lower atmosphere. We conclude that there is a need to more accurately quantify entrainment rates, improve the representation of plume radius, and incorporate the effects of column instability in future versions of 1D volcanic plume models.



## 1. Introduction

To improve our understanding of the physics of volcanic plumes and their interaction with the atmosphere, increasingly sophisticated numerical models of eruptive columns have been developed by a growing number of research groups. These models are different in their design and scope, but all have the fundamental goal of characterizing the dynamics of volcanic plume formation and ultimately providing estimates of source conditions. Descriptions of volcanic columns (or plumes, we use the terms interchangeably in this paper) are important for hazard mitigation because they can be used in models that forecast the dispersion of ash and hazardous gases in the atmosphere. The accuracy of tephra dispersal forecasts is strongly dependent on the source term, which describes both the mass eruption rate of volcanic emissions and their initial vertical distribution in the atmosphere. However, until now there has not been a systematic effort to compare how these source terms are derived. For this study, we have brought together 13 different models to perform a set of simulations using the same input parameters,

http://dx.doi.org/10.1016/j.jvolgeores.2016.01.017
0377-0273/

so that results can be meaningfully compared and evaluated. The motivation is twofold: (1) to provide a conceptual overview of what the various models can accomplish, and (2) to target specific areas for further exploration by the research community as a whole.

## 2. Background on volcanic eruption column models

Numerical models of explosive volcanic eruptions range in complexity from those requiring a computer cluster, to those requiring only seconds on a laptop or web interface. The models used in this study fall into two main categories: one-dimensional (1D) integral models, based on different applications of the mathematical description of turbulent buoyant plumes by Morton et al. (1956), and three-dimensional (3D) models, designed to resolve the detailed turbulence structure of volcanic plumes. Simpler (0th order) empirical scaling relationships also exist. As summarized in Table 1, this study brings together a selection from each of these categories, including 13 different 1D and 3D models. In the following sections, we provide a brief background and description for each.

### 2.1. Empirical scaling relationships (0th order)

These are empirical scaling relationships between plume height and mass eruption rate (MER) based on observed eruptions, some of which include a simplified description of the atmosphere (e.g., Mastin et al., 2009; Degruyter and Bonadonna, 2012; Woodhouse et al., 2013; Carazzo et al., 2014). These relationship and the values used in them are presented in Table 2.

The relationship proposed by Mastin et al. (2009) is calibrated on a dataset of historical eruptions and the wind condition is not described explicitly, although the use of observational data means that the effects of wind are averaged into the calibration.

In contrast, the relationships derived by Degruyter and Bonadonna (2012); Woodhouse et al. (2013), and Carazzo et al. (2014) explicitly account for the effects of wind. The scarcity of observations with corresponding meteorological measurements means that the Degruyter and Bonadonna (2012) and Woodhouse et al. (2013) relationships are calibrated using 1D plume model computations, which have been shown to describe the observational data (Woodhouse et al., 2013). The relationship of Degruyter and Bonadonna (2012) includes the measured atmospheric temperature and wind profile, source thermodynamic properties, and values of the entrainment coefficients. Woodhouse et al. (2016–a) have explicitly included the measured atmospheric buoyancy frequency and source thermodynamic properties (combining Eqs. (28) and (29) of Woodhouse et al. (2013)), and have inverted the expression of Woodhouse et al. (2013) to give the source mass flux as a function of plume height. Carazzo et al. (2014) have used analogue experiments of strong and weak plumes to build relations that take the wind velocity into account.

The variability and uncertainties of the empirical relationships reflect those of field observations, results of 1D models, and experimental results, on which these relationships are based.

### 2.2. One-dimensional integral models

1D volcanic plume models have their origins in the work Wilson et al. (1978) who applied the mathematical description of turbulent buoyant plumes developed by Morton et al. (1956), hereafter referred to as Buoyant Plume Theory (BPT), to explosive volcanic eruptions. Morton et al. (1956) envisioned the eruption column as a time-averaged Boussinesq plume, in which density differences are negligible, except where they give rise to a buoyancy force. The characteristic timescale of the plume is considered to be longer than that of turbulent motion, thereby removing the need to describe the turbulence in detail. Within this framework, Morton et al. (1956) described turbulent mixing as a horizontal inflow of ambient air into the plume, occurring at a rate proportional to the mean vertical velocity of the plume. Furthermore, the ratio of inward horizontal to upward vertical velocity is assumed to be constant at all heights. This assumption allows closure of the evolution equations for the mass (equivalently, volume for an incompressible fluid), momentum, and buoyancy fluxes. BPT assumes self-similarity of the radial profile of the time-averaged plume properties such as the axial velocity and bulk density. Existing models use a range of different profiles, with some assuming a top-hat form, and others a Gaussian (e.g. Davidson, 1986).

Despite their simplicity, 1D models have been remarkably successful at describing buoyant plumes (e.g., List, 1982; Turner, 1986; Linden, 2000; Hunt and van den Bremer, 2010) and continue to be the subject of much research. They have been extended to include the effects of a cross-flow (e.g., Priestley, 1956; Hewett et al., 1971; Briggs, 1975, 1984; Weil, 1988) and moisture (e.g., Morton, 1957; Weil, 1974).

The application of BPT to volcanic plumes requires a relaxation of the Boussinesq assumption as a result of the large density differences between the plume and the environment, large temperature differences, and the large accelerations that occur in volcanic plumes. In addition, models such as those developed by Sparks (1986) who generalized results of Wilson (1978), considered the effect of different phases (ash, gas) on the bulk properties of the plume, and used some of the thermodynamics of compressible gas flows.

The basic equations in most of the 1D models used in the present inter-comparison study are based on Woods (1988) who reformulated the model from the starting point on the basis of the conservation laws. Woods (1988) assumes pressure equal to ambient pressure at a given elevation and gas properties governed by the ideal

**Table 1**
Summary of the models used in the exercise.

| Label | Name | Corr. author | Model type | Air entrainment | Wind | Particle fallout | Particle re- entrain. | Moisture entrain. | Water latent heat | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *Puffin* | M. Bursik | 1D | $\alpha=0.15\ \beta=1.0$ | Yes | Yes | Yes | No | No | 1 |
| 2 | *Degruyter* | W. Degruyter | 1D | $\alpha=0.1\ \beta=0.5$ | Yes | No | No | Yes | Yes | 2 |
| 3 | *PlumeMoM* | M. de'Michieli | 1D | $\alpha=0.09\ \beta=0.6$ | Yes | Yes | No | No | No | 3 |
| 4 | *Devenish* | B. Devenish | 1D | $\alpha=0.1\ \beta=0.5$ | Yes | No | No | Yes | Yes | 4 |
| 5 | *FPluMe* | A. Folch | 1D | $\alpha=f(Ri)\ \beta=g(Ri)$ | Yes | Yes | Yes | Yes | Yes | 5 |
| 6 | *PPM* | F. Girault | 1D | $\alpha=f(Ri)\ \beta=0.5$ | Yes | Yes | No | No | No | 6 |
| 7 | *Plumeria* | L. Mastin | 1D | $\alpha=0.09\ \beta=0.5$ | Yes | No | No | Yes | Yes | 7 |
| 8 | *PlumeRise* | M. Woodhouse | 1D | $\alpha=0.09\ \beta=0.9$ | Yes | No | No | Yes | Yes | 8 |
| 9 | *ASH1D* | M. Cerminara | 1D | $\alpha=0.1\ \beta=0.0$ | No | No | No | No | Yes | 9 |
| 10 | *ATHAM* | M. Herzog | 3D | LES | Yes | Yes | Yes | Yes | Yes | 10 |
| 11 | *SK-3D* | Y. J. Suzuki | 3D | DNS-LES* | Yes | No | No | No | No | 11 |
| 12 | *ASHEE* | M. Cerminara | 3D | LES | No | Yes | Yes | Yes | Yes | 12 |
| 13 | *PDAC* | T. Esposti Ongaro | 3D | LES | No | Yes | Yes | No | No | 13 |

Refs: 1—Bursik (2001); Pouget et al. (2016); 2—Degruyter and Bonadonna (2012); 3—de' Michieli Vitturi et al. (2015, 2016); 4—Devenish (2013; 2016); 5—Folch et al. (2015); Macedonio et al. (2016); Folch et al. (2015); 6—Girault et al. (2014, 2016); 7—Mastin (2007, 2014, this issue); 8—Woodhouse et al. (2013); in this issue); 9—Cerminara (2015); 10—Herzog et al. (1998; this issue); 11—Suzuki and Koyaguchi (2009); Suzuki et al. (2016–a); 12—Cerminara (2015); Cerminara et al. (2016); 13—Esposti Ongaro et al. (2007); Esposti Ongaro and Cerminara (2016); *—see the description of SK-3D in Section 2.3.