Computers & Geosciences 89 (2016) 174–185

Contents lists available at ScienceDirect

Computers & Geosciences

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

Research paper

Parallel simulation of particle transport in an advection field applied to volcanic explosive eruptions

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ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form
27 November 2015
Accepted 5 February 2016
Available online 11 February 2016

Keywords:
Explosive volcanism
Volcanic plumes
Volcanic ash transport
Tephra
MPI
Parallelization

ABSTRACT

Volcanic ash transport and dispersal models typically describe particle motion via a turbulent velocity field. Particles are advected inside this field from the moment they leave the vent of the volcano until they deposit on the ground. Several techniques exist to simulate particles in an advection field such as finite difference Eulerian, Lagrangian-puff or pure Lagrangian techniques. In this paper, we present a new flexible simulation tool called TETRAS (TEphra TRAnsport Simulator) based on a hybrid Eulerian–Lagrangian model. This scheme offers the advantages of being numerically stable with no numerical diffusion and easily parallelizable. It also allows us to output particle atmospheric concentration or ground mass load at any given time. The model is validated using the advection–diffusion analytical equation. We also obtained a good agreement with field observations of the tephra deposit associated with the 2450 BP Pululagua (Ecuador) and the 1996 Ruapehu (New Zealand) eruptions. As this kind of model can lead to computationally intensive simulations, a parallelization on a distributed memory architecture was developed. A related performance model, taking into account load imbalance, is proposed and its accuracy tested.

1. Introduction

Explosive volcanic eruptions are typically associated with the injection into the atmosphere of large amounts of particles (known as tephra) dispersed over long distances depending on size, shape and density. Accumulation at ground level of few millimeters to tens of centimeters of tephra can cause a wide range of hazards including collapse of roofs, damage to crops, killing of many grazing animals, contamination of water supplies, disruption of electricity and telecommunication networks and perturbation of ground transportation, while fine volcanic ash ($<63\ \mu m$) significantly threatens aviation operations and human health (Horwell and Baxter, 2006; Guffanti et al., 2008; Casadevall, 1994; Wardman et al., 2012; Wilson et al., 2009, 2012). Consequently, even though other volcanic phenomena are more likely to directly endanger human life (e.g. pyroclastic density currents and lahars), tephra dispersal and sedimentation can seriously impact entire economic sectors and disrupt critical infrastructure services, as demonstrated by the recent eruptions of Eyjafjallajökull (Iceland; 2010 Gudmundsson et al., 2010) and Cordón Caulle (Chile; 2011 Wilson et al., 2012) volcanoes.

During the past decades, several Volcanic Ash Transport and Dispersal Models (VATDMs) have been developed with variable levels of complexity and different objectives mostly including (i) a better understanding of particle transport and sedimentation dynamics; (ii) the compilation of real-time and long term hazard assessment associated with both ground load and atmospheric concentrations of ash; (iii) and the determination of eruption source parameters through inversion strategies (see Folch, 2012; Bonadonna and Costa, 2013; Bonadonna et al., 2011 for a review).

Most existing VATDMs are either Eulerian finite difference schemes such as FALL3D (Costa et al., 2006; Folch et al., 2009) or Lagrangian particle-puff schemes such as VOL-CALPUFF (Barsotti et al., 2008; Barsotti and Neri, 2008) or NAME III (Jones et al., 2007). Some are pure Lagrangian models such as PUFF (Searcy et al., 1998).

Pure Lagrangian models dealing with point particles have the advantage of allowing the implementation of individual particle behaviour as well as particle interaction. Moreover, they remain unconditionally stable, unlike for example finite difference schemes, and allow to monitor ash concentration in the atmosphere as well

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http://dx.doi.org/10.1016/j.cageo.2016.02.005
0098-3004/

as ground mass load at any given time. The drawback is that such representations require the simulation of large numbers of particles to yield statistically accurate results. This may thus produce very computationally intensive simulations. Although the increasing computational capacities of computers and supercomputers tend to make these simulations affordable, parallelization still remains essential to run them on large numbers of computing cores. However, pure Lagrangian models are difficult to implement on massively multicore systems when particle interactions are involved. This is why we propose an implementation based on a hybrid model.

In this paper, we present a new hybrid Eulerian–Lagrangian model for the dispersal and sedimentation of tephra with an emphasis on computational efficiency and model flexibility. Computational efficiency is particularly important for both real-time forecasting and long-term hazard assessments. In our approach, particles remain linked to a site and their exact positions are continuously tracked. This allows for an accurate treatment of diffusion while maintaining a known maximum spatial integration step. The associated data structure facilitates a parallel implementation as well as the addition of complex sedimentation processes, such as particle aggregation (Brown et al., 2012; Costa et al., 2010). The implementation was designed with a modular approach to permit modification or addition of components to the physical model. It is then possible to use our simulation tool both for the study of the dynamics of particle dispersion and as a prediction tool for hazard assessment. As previously said, our model allows us to easily monitor both atmospheric ash concentration and ground mass load. In this paper, we only focus on the latter.

2. Physical model description

During explosive volcanic eruptions, a hot mixture of particles and volcanic gases is typically ejected with an initial density several times larger than in the atmosphere, and rises due to momentum. As the ejected material entrains ambient air, the mixture density drastically decreases and the eruptive plume starts rising due to buoyancy. If the plume upward velocity is much larger than the horizontal wind velocity (strong plume, Fig. 1a), the volcanic plume buoyantly rises up to the neutral buoyancy level (H_b) where it starts spreading laterally as a gravity current (umbrella cloud). In contrast, if the horizontal wind velocity dominates, the plume bends over above the basal jet before spreading laterally around the neutral buoyancy level (weak plume, Fig. 1b) (Bonadonna and Phillips, 2003; Carey and Sparks, 1986). In all cases, cloud spreading results from the interplay between buoyancy and wind advection, with the contribution of buoyancy being proportional to plume height (Bonadonna and Phillips, 2003; Bonadonna et al., 2015; Costa et al., 2013).

The physics of plume dynamics and rise is described in Degruyter and Bonadonna (2012). The model main parameters include the wind speed at the tropopause, the initial plume velocity U_0, temperature θ_0 and radius r_0, and the initial mass fraction of exsolved volatiles n_0. The model then outputs the mass eruption rate and plume profile by giving the position, angle with horizontal, radius of the plume and speed at each point of the plume. The total erupted mass is derived directly from the mass eruption rate and the eruptive events durations. Depending on their size and density, particles are transported upward by the volcanic plume and, if sufficiently small, might be entrained within the umbrella cloud and sediment according to their terminal velocity. In particular, information on the Total Grain-Size Distribution (TGSD), namely the size distribution of particles injected into the atmosphere, combined with particle density is necessary to initialize the model.

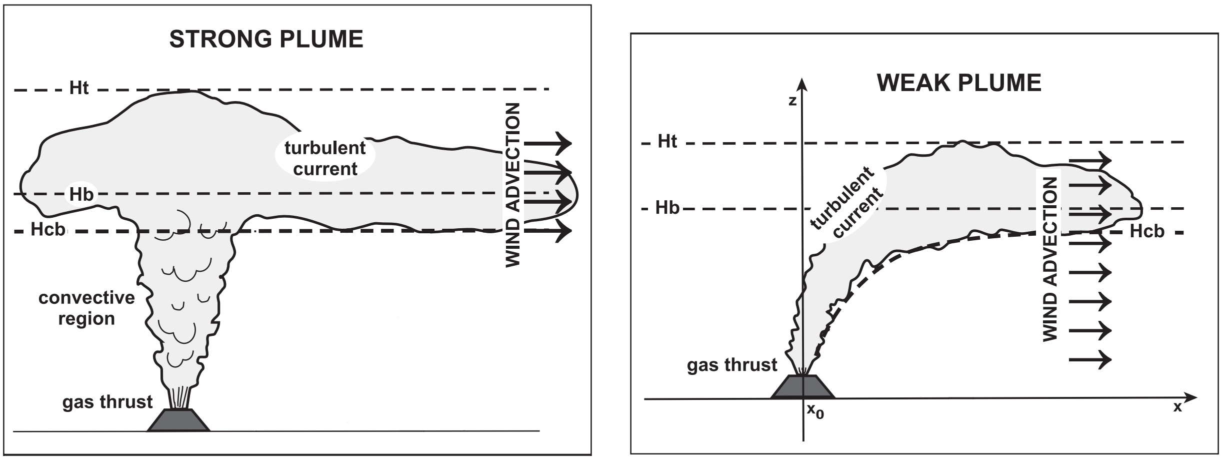
Turbulent effects, which play an important role in this model, are represented through a diffusion process. Different diffusion coefficients are applied in the atmosphere (D_a) and in the plume (D_p), the latter coefficient being usually several times larger.

We divide space into three main zones (Fig. 2), where the velocity fields are described as

- atmosphere: $\vec{u} = \vec{u}_s + \vec{u}_w + \vec{u}_{ra}$;
- volcanic column: $\vec{u} = \vec{u}_s + \vec{u}_w + \vec{u}_p + \vec{u}_{rp}$;
- umbrella cloud: $\vec{u} = \vec{u}_s + \vec{u}_w + \vec{u}_b + \vec{u}_{ra}$;

where

- $\vec{u}_s$ is the settling velocity of the particles (Bonadonna and Phillips, 2003; Kunii and Levenspiel, 1991);
- $\vec{u}_w$ is the wind velocity, retrievable from analytical models (Carey and Sparks, 1986; Holasek and Self, 1995), weather reanalysis databases or weather forecasting models;
- $\vec{u}_p$ is the plume velocity (Degruyter and Bonadonna, 2012);
- $\vec{u}_b$ is the spreading velocity of the umbrella cloud due to buoyancy (Bonadonna and Phillips, 2003);
- $\vec{u}_{ra}$ and $\vec{u}_{rp}$ are random velocities for simulating diffusion in the atmosphere and in the volcanic column, respectively.



(a) (b)

Fig. 1. Representation of the main features of (a) a strong plume and (b) a weak plume (adjusted from Bonadonna et al., 2005). H_b: Neutral buoyancy level; H_t: total plume height.