

Author's response: general comments

Dear Editor, dear colleagues,

we would like to thank Dr. Arnau Folch and Dr. Antonio Costa for their thorough reviews and useful comments.

We accept their invitation to try to make the paper more readable for a wider audience, somehow reducing the mathematical sections. To do this, we have rewritten the model presentation and moved some more technical parts of Section 2 to two new appendixes, in order to make the reading more fluent.

On the other hand, the two reviews are somehow opposite in their suggestion to cut or reduce specific parts of the paper. Coherently with GMD aims, we have made the choice to focus the paper more on the evaluation of the new model, thus reducing the discussion of the volcanological application, to which future works will be devoted on more targeted journals. Therefore, Section 4 is left mostly unvaried (see Response to Referee-1), while Section 5 has been reduced, by limiting it to the demonstration of the ability of the model to reproduce the large-scale behaviour of weak volcanic plumes and to a demonstration on the effect of the spatial resolution in Large-Eddy Simulations at the geophysical scale.

Comment by Referee-1 (A. Folch)

This paper describes a new Eulerian model for non-equilibrium dynamics of gas-particle mixtures valid for low concentration regimes and particle Stokes number. However, it describes gas-particle non-equilibrium effects including clustering of particles by turbulence. The model has been implemented to OpenFOAM and applied to LES simulations of volcanic plumes in a stratified atmosphere, describing important features such as air entrainment, buoyancy reversal (i.e. transition from jet to buoyant plume or generation of PDCs), or maximum plume height. The modelling of first-order non-equilibrium effects (Equilibrium Eulerian approach) supposes an improvement with respect to a 3D dusty gas model or relaxations of it (e.g. ATHAM model), but without the higher computational cost associated to full N-phase models. This is a really nice and rigorous paper that certainly deserves publication. I only have some suggestions requiring minor to moderate revision.

1. A Table compiling all the symbols appearing in the equations is necessary.

2. *Section 2 presents first the full multiphase equations (2.1), the equilibrium-Eulerian approach (2.2) and finally its LES version (2.3). This makes the section very long and not easy to follow. My suggestions would be: i) remove section 2.1 (equations are actually not new and can be found elsewhere, e.g. Cerminara 2015), ii) start by presenting directly the set of eq. (29) and then explain the meaning of variables and approaches, and iii) write down the LES equations (38) directly and, if necessary, move its derivation to an appendix. These changes would shorten the section and prevent some readers to get lost before reaching section 3...*
3. *A similar argument applies to Section 4, where up to 4 validation examples are presented. Results are very nice, but devoting up to 14 pages and 7 figures seems excessive. I agree that all these model validation tests have to be mentioned but the degree of detail may deviate attention. I suggest to largely simplifying (or removing) 4.1 and 4.2, which are not essential for the application focus of the paper. In contrast, section 4.3 is wonderful in terms of volcanic plumes. The parts regarding HPC model performance and strong scalability analysis (e.g. Fig 1) could be moved to Section 3.*
4. *Section 5 is also very nice. I found particularly interesting the use of ASHEE to calibrate much simpler 1D plume models. Further work on this would be very welcomed by the community.*
5. *The conclusions end up as (the model) reproduce the non-equilibrium behavior of gas-particle mixtures with a limited computational cost. This statement contrasts with the 25 days required to simulate 720s using 1024 CPUs (section 5)! Some discussion on mesh refinement versus accuracy (and convergence) would be worth.*

Detailed response to Referee-1 (A. Folch)

1. We have added a table in Appendix A, with symbols and notations.
2. We have shortened Section 2, by moving the derivation of the Equilibrium-Eulerian and the LES formalism in Appendix. At the same time, the former Appendix A (now Appendix C) has been shortened.

3. Concerning the level of detail of Section 4, we think that a comprehensive presentation of the numerical tests is necessary and one of the main objectives of the paper. We have stated this more clearly also in the paper introduction. We believe indeed that the volcanic plume model would not be credible if its ability to reproduce the variety of phenomena characterizing the atmospheric dynamics of pyroclastic dispersal is not demonstrated. In this context, the capability of accurately simulating multiphase turbulence is of the greatest importance. Removing Sections 4.1 and 4.2 would leave the question of the suitability of the model to describe gas-particle turbulence unanswered. Section 4.1 indeed demonstrates that the adopted numerical scheme is accurate enough to correctly reproduce a turbulent spectrum (in simplified geometric conditions) in a Direct Numerical Simulation. Section 4.2 demonstrates that the model can properly describe the effect of solid particles on the turbulent flow field. Section 4.3 demonstrates that Large-Eddy Simulation is suited to describe the dynamics of a turbulent buoyant plume. The level of detail in the presentation of these benchmarks guarantees their reproducibility for future model inter-comparison studies. Finally, Section 4.3 testifies the ability of the model to reproduce supersonic regimes, which are also typical of explosive eruptions.

Consistently with GMD terminology, we have changed the title of Section 4 into *Model verification and evaluation*.

4. We have chosen to focus the paper more on the evaluation of the model adequacy than on the volcanological application. This choice was also driven by Referee-2 comments. We thus have slightly reduced Section 5, presenting the volcanological application, but we have kept the comparison with simpler 1D models.
5. One of the most challenging aspects of volcanic plume simulations is the multiscale nature of the phenomenon. The required grid size at the vent (which constrains the numerical time-step) is about four orders of magnitude smaller than the integral length scale. Therefore, volcanic plume simulation would always require a large number of computational cells and a small time-step, thus making the computational cost high. The “limited computational cost” of 3D numerical simulations is therefore referred to a comparison with Eulerian-Eulerian models and should not be taken as an absolute indication. Anyway, we have reported the execution time of 3D simulations on a low-res numerical

grid, showing that overall satisfactory results can be obtained in about one day on a personal computer.

6. Typos have been corrected and all editing reviews have been accepted.

Pg8920, Lines 8-11. Why stabilization of convection is unnecessary in your formulation?

Because stabilization of convection is given by the LES models. The term discussed in these lines is added in OpenFOAM to further improve the stabilization of the theoretical algorithm in meshes with very low resolution.

Comment by Referee-2 (A. Costa)

This is an excellent manuscript of high scientific quality presenting a new volcanic plume model able to describe the non-equilibrium dynamics of eruptive plume mixture. The formulation is rigorous and the assumptions and limitations of the model clearly stated. Moreover a few tests are simulated and described in order to validate and show the performance and the code.

However the presentation style is a bit too technical and mathematical for GMD and volcanological audience and I would suggest improving the presentation quality where possible.

I have also a few specific comments that I have listed below:

1. *In the Abstract citations should be avoided unless strictly necessary; in this case I reckon they may be removed; line 18: “able to reproduce their observed averaged and ...” → “able to reproduce the averaged and...”*
2. *Pag. 5, lines 18-20: sentence a bit confused, I would rephrase the sentence as “Above that level, the plume rises up to its maximum height and then starts to spread out as a gravity current (e.g. Costa et al., 2013) forming an umbrella ash cloud dispersing in the atmosphere...”*
3. *Pag. 7: Add reference after “Sods shock tube problem”;*
4. *Pag. 8: in order to avoid confusion using similar symbols ($\hat{\rho}_s$ and ρ_s) I would use ρ_b to denote bulk density;*
5. *Pags. 9-10: Eq. (4) is valid for spherical particles only (Ganser, 1993). Tephra particles can differ significantly from spheres and terminal settling velocities of volcanic particles be up to a factor 2-3 with*

respect spherical assumption (e.g. Dellino et al., 2005; Pfeiffer et al. 2005). Although for the aim of the manuscript is not necessary to change the assumption of spherical particles, the limitations of this assumption should be commented and also the effects of particle sphericity and variation of air density and viscosity with altitude on the estimations Re_s etc should be discussed;

6. Section 5: This part can be a bit shortened referring to other works of the authors where simulations are discussed in more detail (e.g. Suzuki et al, submitted; Cerminara et al., submitted)

REFS Cerminara, M., Esposti Ongaro, T., Neri, A., (submitted). Large-eddy simulation of kinematic decoupling and turbulent entrainment in volcanic gas-particle plumes. Submitted to *J. Volcanol. Geoth. Res.*

Costa A., Folch A., Macedonio G. (2013) Density-driven transport in the umbrella region of volcanic clouds: Implications for tephra dispersion models, *Geophys. Res. Lett.*, Vol. 40,

Dellino, P., Mele, D., Bonasia, R., Braia, L., La Volpe, L., Sulpizio, R., 2005. The analysis of the influence of pumice shape on its terminal velocity. *Geophysical Research Letters* 32 (L21306) doi:10.1029/2005GL023954.

Ganser, G., 1993. A rational approach to drag prediction of spherical and nonspherical particles. *Powder Technology* 77, 143152.

Pfeiffer T., Costa A., Macedonio G. (2005) A model for the numerical simulation of tephra fall deposits. *J. Volcanol. Geotherm. Res.*, Vol. 140: 273-294, doi: 10.1016/j.jvolgeores.2004.09.001

Suzuki, Y.J., Costa, A., Cerminara, M., Esposti Ongaro, T., Herzog, M., Van Eaton, A., Denby, L.C., (submitted). Inter-comparison of three-dimensional models of volcanic plumes. Submitted to *J. Volcanol. Geoth. Res.*

Detailed response to Referee-2 (A. Costa)

We have reduced the mathematical parts and moved the more technical parts of the derivation of the Equilibrium-Eulerian model to the Appendix (new Appendixes B and D), in accordance also to Referee-1 comments (see Section above).

1. We have removed the references in the abstract.
2. We have rewritten the sentence as suggested.

3. We have added a reference to Sod (1978) original paper.
4. We fear that adding a second subscript (the first is used to indicate the solid or gaseous component index) would generate more confusion, so we have kept the original notation.
5. We have commented about the possible modifications to account for non-spherical particles in Eq. (4) and added the suggested references.
6. We have shortened Section 5. In detail, we have reported only the specific study on the effect of the grid size (which is essential to the model evaluation study) leaving the discussion of the application to future papers.

Main changes in manuscript

1. The release version of the model ASHEE-1.0 has been added to the title.
2. Section 2 has been shortened by moving parts of Sections 2.1 and 2.3 to the Appendix. In particular the former system of Eqs. 10 has been moved in the Appendix B (Eqs. B1) and substituted by former Eqs. 29.
3. New appendixes A (list of symbols); B (Eulerian-Eulerian model and derivation of the mixture formulation); D (discussion of the LES approach). Appendix C has been shortened.
4. We have moved the discussion on the parallel performance to the new section 3.1.
5. Section 5 has been slightly reduced. Figure 18 has been reformatted to make it more readable. Figure 19 has been removed. Only panel a) of Figure 21 (Figure 20) has been maintained, to improve readability and make the comparison with Fig. 11 more immediate. A new figure (new Fig. 21) has been introduced to illustrate the effect of the grid resolution on just the volcanic plume radius and velocity.