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Geoscientific Model Development Discussions

Interactive comment on "PLUME-MoM-TSM 1.0.0: A volcanic columns and umbrella cloud spreading model" *by* Mattia de' Michieli Vitturi and Federica Pardini

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This paper presents an extension of the PLUME-MoM model for volcanic plumes and umbrella clouds. The advances occur in two main areas. Firstly, improvements are made to the existing PLUME-MoM description of the rising eruption column, specifically in the description of water phase changes and particle aggregation in the rising plume. Secondly, this model for the rising plume is coupled to an existing depth-integrated model for the spreading of umbrella clouds.

The overall approach of the paper is of reduced order modelling based on aspect ratio; the rising plume is assumed to be much thinner than it is tall, allowing the description of

a steady-state plume using one-dimensional ordinary differential equations. Similarly, the umbrella cloud is assumed to be much thinner than its horizontal extent, allowing depth-integrated two-dimensional equations to be used to describe its horizontal motion. This reduced order modelling approach is very well established, and results in models which are physically derived but can be run very quickly compared to full three-dimensional simulations; this facilitates operational use.

The improvements in the description of water and particle aggregation in the rising eruption column are useful additions to that area of modelling. While the indication from Costa *et al.* (2016) intercomparison study is that these effects have relatively little influence on the plume height, improved modelling of the particle size distribution in the plume is important for providing source terms to volcanic ash transport and dispersion models.

The umbrella cloud modelling in this paper is based on the depth-integrated (or 'shallow-water') equations, which provide a physically-derived description of the umbrella cloud shape and internal velocity field. A major strength of this approach is that, like the eruption column model, it accounts in a consistent way for the influence of wind on the umbrella cloud. This is a significant advantage over models based on the $r \sim t^{2/3}$ scaling of Woods & Kienle (1994), which is derived around the underlying assumption of an axisymmetric umbrella cloud and so is of very limited relevance when the cloud is influenced by wind.

However, I have some significant concerns over the way in which the umbrella cloud model in particular is used and validated in this paper.

1. As the authors state, the depth-integrated umbrella cloud model (equation 40) closely follows the approach of Baines (2013) and Johnson *et al.* (2015). In particular, the model for drag between atmosphere and the umbrella cloud used in both these papers is also used here to couple the ambient wind field to the motion of the umbrella cloud. The value of the drag coefficient C_D is inferred

in this paper by comparing model outputs with measurements of the 'equivalent radius' of the plume of the April 2015 Calbuco eruption, and a value $C_D = 1$ is selected on this basis.

This value is extremely large – between $100\times$ and $1000\times$ larger than previous studies of gravity currents and intrusions into stratified fluids indicate. It is worth noting that C_D is not a 'free' parameter that is expected to be $O(1)$ (such as the parameter λ in the scaling of Woods & Kienle (1994)), but arises from a physical process, namely the formation of shear layers between the ambient and umbrella cloud. As such it has been constrained experimentally (e.g. https://doi.org/10.1080/00221687909499572). From such experiments, Baines (2013) and Johnson *et al.* (2015) both infer coefficients in the range $C_D = 0.001$ to 0.01. These small values are reflected in the fact that drag forces are usually neglected entirely in models of spreading intrusions (https://doi.org/10.1201%2F9781584889045). As a consequence of the small drag coefficient, both Baines (2013) and Johnson *et al.* (2015) reason that drag becomes significant only late into the eruption (after at least 3 hours for $C_D = 0.01$, 30 hours for $C_D = 0.001$) and very far downwind from the source. This contrasts with the present model, where the much higher drag coefficient results a drag-dominated flow everywhere, with drag nearly arresting the upwind flow after ~ 30 minutes.

- Can the authors comment on why the inferred drag $C_D = 1$ is so much larger than previous studies indicate?
- What physical mechanism is anticipated that could lead to such a large drag force in a high Reynolds number turbulent flow?
- What would be the effect of choosing a drag coefficient in the range $C_D = 0.001$ to 0.01 as previous authors have?
- What changes to the mass flux, or other parameters, would be needed for the model to fit observations with these smaller drag coefficients?

- With a drag coefficient consistent with previous works, is the PLUME-MoM-TSM model able to predict both the altitude and horizontal extent of the Calbuco umbrella cloud simultaneously?

2. The drag coefficient here is inferred from comparison between the model predictions and the umbrella cloud of the second phase of the April 2015 Calbuco eruption (figure 7). The measurements of the Calbuco plume used are the equivalent radii reported by van Eaton *et al.* (2016), in which the area of the umbrella cloud as viewed from the GOES-13 satellite, is converted into the radius of a circle of the same area. This equivalent circle methodology is appropriate for van Eaton *et al.* (2016), where the umbrella cloud is assumed to be a circle, but is less suitable for the present paper, which makes predictions of the full cloud shape. A comparison of the full predicted shape of the cloud with the GOES-13 observations (available in the supplementary material of van Eaton *et al.* (2016)) would provide a much more convincing validation of the model. In particular, the upwind spreading distance is a focus of this paper (in §3.2), but this quantity not validated by the comparison of equivalent radius alone in figure 7.

   - How does the predicted upwind spreading distance in figure 7 compare with measurements of the upwind spread from GOES-13 data?
   - Are the model predictions of the cross-wind plume width and downwind spreading distance consistent with the observations?

3. In §3.2, an approximate expression for predicted upwind spreading distance is given (47). Similar predictions of the upwind spreading distance, in the absence of a rising plume, have been obtained by Baines (2013). How do the predictions of this paper compare to those of Baines (2013)?

   The expression (47) has some pathological properties – for example, a finite upwind spreading distance is predicted even if there is no wind, and the cloud is assumed to spread upwind (positive upwind spreading distance) even for arbitrarily small mass fluxes and high velocities, where a weak plume with no upwind spread is expected. As noted in the previous two points, I have serious concerns about the usefulness of the prediction (47), as is obtained using a drag coefficient that is likely far outside the range of validity of the model equations (40), and is not directly validated. This notwithstanding, equations (47) and (48) need a clear statement of the range of parameters over which they can be used.

Other points:

- line 10: “to compute” → “computation of”
- line 31: “quantity” → “quantities”
- line 58: “sometime” → “sometimes”
- line 107: “context” → “contexts”
- line 120: “detail” → “details”; remove “of the”.
- What is the origin of equation (13)?
- line 227: “collisions” → “collision”
- line 355: Strictly, the transition between rising plume and umbrella cloud is not properly described by either the rising plume or the shallow water model for the umbrella cloud, because the aspect ratio of the flow in this region is not small in either direction. This region, characterised by the plume rising to an overshoot and then descending to the neutral buoyancy level, is likely to be highly turbulent. Implicit in the source terms used in (40) is the assumption that energy associated with horizontal momentum is conserved, but energy associated vertical momentum is lost, in the transition from rising plume to umbrella cloud. Some comment

about the approximations made in this region, and their potential effect on the model results, would be valuable.

- Figure 4 is missing a scale for contour colours. Are the displacements of contours in the lateral and oblique views representing half the thickness of the intrusion h (which should be centered around neutral buoyancy level)?
- In the computations of figure 8, the grain size distribution is divided into a fairly large number of bins (~ 12) with a constant kernel. What are the advantages in this case of the TSM method over a sectional/discrete description of the particle size distribution? In the limit of a very large number of bins in the grain size distribution, would the TSM method produce the same result as a section/discrete description?
- line 606: “wincreasing” → “increasing”

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