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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

Mattia de' Michieli Vitturi and Federica Pardini

mattia.demichielivitturi@ingv.it

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Reply to Reviewer RC2

We thank the reviewer for the comments and the suggestions, which we believe contributed to improve the manuscript. In particular, the comments about the value of drag coefficient previously estimated let us consider a wider range of values to investigate, and a different criteria to select the "best value", which is now more consistent with literature results. We collected below the main comments of the reviewer in several points (in bold), to which we replied in detail (our replies in italics). In addition, the reviewer can find in the GMD online discussion a pdf of the revised manuscript, where

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the changes with respect to the previous version have been highlighted.

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 CD 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 CD = 1 is selected on this basis. This value is extremely large – between 100× and 1000× larger than previous studies of gravity currents and intrusions into stratified fluids indicate. It is worth noting that CD 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 CD = 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/10.12012F9781584889045). 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 CD = 0.01, 30 hours for CD = 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 âĹij 30 minutes.

- **Can the authors comment on why the inferred drag CD = 1 is so much larger than previous studies indicate?**

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- **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 CD = 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-MoMTSM model able to predict both the altitude and horizontal extent of the Calbuco umbrella cloud simultaneously?**

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?**

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We thank the reviewer for letting us notice the problem with the high value of the drag coefficient. For this reason, we performed new simulations and compared the results obtained with CD=1, 0.1 and 0.01. With respect to the version of the manuscript originally submitted, we compared not only the "equivalent radius", but also the upwind spreading, manually extracted from the Van Eaton et al. 216 paper. This quantity provides a better comparison between observation and numerical results for two reasons. The first is that the upwind spreading is the main quantity of interest of our work, and in particular it is the one for which we try to provide an analytical relationship with some characteristic quantities of the rising plume. The second is that in our simulations of the umbrella cloud spreading we use a constant wind, extracted at the vent coordinates from the ECMWF-ERA5 reanalysis dataset. Thus, upwind spreading, which occurs close to the vent, is less affected by this approximation than the umbrella cloud area, which covers locations far from the vent, and where wind could be potentially quite different. Thus, we completely agree with the reviewer that the equivalent radii reported by van Eaton et al. (2016) are not the best data to use to calibrate the drag coefficient.

Indeed, the new calibration, based on observation of upwind spreading, shows that CD=0.1 gives better results than CD=1 and CD=0.01 for both the phases (see plots above). This result is consistent with the values obtained in Pouget et al. 2016 for several eruptions. In the new version of the manuscript we present these new results (please see the new Figures at the end of this reply) and we discuss more in detail previous results on the value of the drag coefficient. The text has been modified in the following way:

> *"For both phases, the outputs at the neutral buoyancy level of the plume model of PLUME-MoM-TSM (volumetric flow rate, radius and horizontal velocities) were used as input of the umbrella cloud module. For this application, we varied the drag coefficient C_D of the umbrella cloud model in order to find the value which best reproduced the spreading in the atmo-*

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sphere observed during the eruption. From the experiments of Abraham et al. (1979), Baines (2013) and Johnson (2015) both inferred coefficients in the range C_D=0.001 to 0.01, while Pouget et al. (2016), by comparing the results of the shallow-water intrusion model developed by Johnson (2015) with satellite data from seven eruptions, better reproduced observations of umbrella cloud structure and morphological evolution with a value C_D=0.1, which was the largest value of the investigated range. Here, three values were tested (C_D=0.01, 0.1 and 1) by carrying on the simulations for 1.5 hour and 2 hours for the first and second phase, respectively. At each time step we computed: (i) the upwind spreading, defined here as the maximum horizontal distance from the vent in the opposite direction to that of the wind at the neutral buoyancy level; (ii) the radius of a circle with area equivalent to that of the modeled umbrella cloud."

"These values are plotted, at intervals of 300 s, in the left panels of Fig. 7, with blue lines for the equivalent radius and red lines for the upwind distances. In the right panels of Fig. 7 the edges of the umbrella cloud at the end of the simulations are plotted, with different lines for the different values of C_D. From both the left and right panels we can observe the expected larger spreading of the umbrella cloud for smaller values of C_D. These results highlight the fact that intrusive gravity current dominates in the initial stages of the dispersion of tephra at the neutral buoyancy level and large upwind and crosswind spreadings of the umbrella cloud with respect to the vent location (denoted with a yellow star in the right panels of Fig. 7) are produced also for subplinian eruptions. In order to constrain the value of the drag coefficient, the blue lines in the left panels of Fig. 7 are compared with the series of values for the umbrella radius reported in Van Eaton et al. (2016), obtained detecting the edge of the umbrella from GOES-13 satellite images and here plotted with blue markers. From the results plotted in

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the figure, we can see that the values obtained with C_D*=1 seem to better match the observations, with a small overestimate at the beginning and a small underestimate at the end of the simulation.*

A different result is obtained by analyzing the modeled upwind spreading of the umbrella cloud. First of all, we can see from the red lines in the left panels of Fig. 7 that for values of C_D *greater than 0.1, a steady upwind distance is approached at the end of the simulation, and that by changing (increasing or decreasing) the drag coefficient by an order of magnitude, the upwind spreading at the final time changes approximately by a factor 2. In this case, when model results are compared with the upwind spreading derived from the processing of the observations presented in Van Eaton et al. (2016), represented by the red crosses in the left panels of Fig. 7, we see that the drag coefficient value* C_D*=0.1 produces the best results. The two different values of* C_D *obtained by comparing the equivalent radius and the upwind spreading with observational data can be due to the several approximations in the numerical simulations. In particular, the depth-averaged umbrella cloud model uses a constant wind (in time and space), extracted at the vent coordinates and at the neutral buoyancy level from the ECMWF-ERA5 reanalysis data. Thus, while upwind spreading, which is measured close to the vent, is slightly affected by this approximation, the spreading of the whole umbrella cloud (controlling the equivalent radius) could be affected by larger errors, because downwind wind far from the vent can be different from the assumed constant value. Furthermore, we notice that the value* C_D*=0.1 better agrees with the results presented in Pouget et al. (2016). For these reasons, and because in the following of the paper we are mostly interested in quantifying the upwind spreading of the umbrella cloud, we use the value* C_D*=0.1 as reference value. For this value of the drag coefficient, umbrella cloud thickness at the end of the simulations is plotted*

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> *for both the phases in Fig. 8. The larger volumetric flow rate injected at the neutral buoyancy level for the second phase resulted in a thicker cloud, with a total height of column and umbrella of approximately 15.5 km and 17.5 km above sea level for the first and second phase, respectively. These values compare well with those reported in Van Eaton et al. (2016)."*

In addition, because of the new value of CD, all the simulations for the sensitivity analysis and the fitting of the analytical relationship have been redone, providing new results where the upwind spreading increases by almost a factor 2, and in consistent way for all the input parameters, with respect to the results presented in the first version of the manuscript. In any case, we observe that the value of CD obtained with the comparison of Calbuco observations is still higher than those inferred by Baines (2013) and Johnson et al. (2015). This is now discussed also at the end of Section 3.2:

> *"We also remark that the values of the upwind spreading presented here are strongly dependent on the drag coefficient CD, in this analysis fixed at 0.1, and that the lower values suggested by (Baines, 2013) and (Johnson et al., 2015) would produce a larger upwind spreading of the umbrella cloud. Additional simulations we performed (not shown here) suggest that a decrease of the drag coefficient of one order of magnitude results approximately in doubling the upwind spreading distance."*

We also remark that the reviewer could notice in the plots some very small differences in the results obtained for the case C_D*=1, with respect to the results presented in the previous version of the manuscript for the same value. This is because Reviewer 1 noticed a minor thing to fix in the plume model, which can also affect the predicted neutral buoyancy level and thus the input parameters of the umbrella cloud model.*

REF. Pouget, S., Bursik, M., Johnson, C. G., Hogg, A. J., Phillips, J. C., & Sparks, R.

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S. J. (2016). Interpretation of umbrella cloud growth and morphology: implications for flow regimes of short-lived and long-lived eruptions. Bulletin of Volcanology, 78(1), 1.

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.

As previously written, the comment of the reviewer helped us in making a more convincing calibration of the drag coefficient, which provided a lower value which agrees with that presented in previous works. The reviewer is also correct when he states that the original expression had some pathological properties, in particular for the finite upwind spreading without wind. We really thank him because his observation suggested to us to search for a different expression, for which the correct behaviour with no wind is predicted:

$$z = a\frac{x^b}{y^c} \tag{1}$$

where z is the upwind spreading, x is the mass flow rate and y is the wind velocity, and a,b,c are three fitting parameters.

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The new expression still provides a good coefficient of determination (>0.98) and small relative errors over the whole range of parameters investigated. The same expression has been used for the other fitting, because the downwind distance acts as the wind, and upwind distance cannot be finite when it goes to zero. Also in this case good coefficient of determination and small relative errors in the predicted upwind spreading are obtained. As already written in the reply to the previous comment, we remark that the reviewer could notice in the plots some very small differences with respect to the results presented in the previous version of the manuscript for the same values. This is because Reviewer 1 noticed a minor thing to fix in the plume model, which can also affect the predicted neutral buoyancy level and thus the input parameters of the umbrella cloud model.

Other points:

line 10: "to compute" → "computation of"

Done.

line 31: "quantity" → "quantities"

Done.

line 58: "sometime" → "sometimes"

Done.

line 107: "context" → "contexts"

Done.

line 120: "detail" → "details"; remove "of the".

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Done.

What is the origin of equation (13)?

We added the reference to Bursik et al. 1992. Our equation is slightly different from that of the original reference, because of the presence of a multiplying factor 2 in the original one (Eq. 19 in Bursik et al. 1992). This is due to the fact that we have the factor 2 in our Eq. 13, while it is missing in Eq. 16a in Bursik et al. 1992. We preferred to keep it in the equation and not in the equation for p because this factor come from the integration along the edges of the plume, which results in the $2\pi r$ *term on the right-hand side of Eq.13.*

line 227: "collisions" → "collision"

Done.

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.

Following the suggestion of the reviewer, we added the following text after the description of the link between plume model and umbrella cloud model:

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> *"It is important to observe that the transitional region between rising plume and umbrella cloud, characterised by the plume overshoot and then the descent to the neutral buoyancy level, has an aspect ratio of the flow not small in either direction, and is likely to be highly turbulent. For these reasons, this transition region is not properly described by either the rising plume or the shallow water model for the umbrella cloud, and the derivation of the inflow of the umbrella cloud model directly from the output of the plume model at the neutral buoyancy level represents a simplification of the real dynamics."*

As regards the kinetic energy associated with horizontal and vertical momentum, we observe that even without the radial contribution associated to the term dr/dz and to the plume horizontal velocity at the nbl, at the boundary of the source area we still have a kinetic energy which is due only to the source term in the mass equation. In fact, the source term produces a thickness in the source area, which spreads laterally because of gravity, with a volumetric flow rate consistent with that of the plume at the nbl.

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)?

Thank you for the comment, we now specified in the caption that this plot and the different colors are not meant to represent quantitatively any property of the umbrella, but only to distinguish the different contours.

In the computations of figure 8, the grain size distribution is divided into a fairly large number of bins (âĹij 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

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description?

The problem with a sectional/discrete description is that aggregation could produce sizes which do not correspond to the sizes represented by the discrete bins. For example, if the characteristic sizes of the bins are 1,2 and 4 mm, then their volumes are of the order of 1,8 and 64 cubic mm. If two particles of 1mm aggregate, they would produce an aggregate of 2 cubic mm. Now, if we choose to assign to the newly formed aggregate the size which has the closer volume among the characteristic sizes, it will remain in the 1mm bin. So, we would ignore the aggregation. The TSM method allows to have a distribution within each bin, and the distribution changes also with intra-bin aggregation.

line 606: "wincreasing" → "increasing"

Done.

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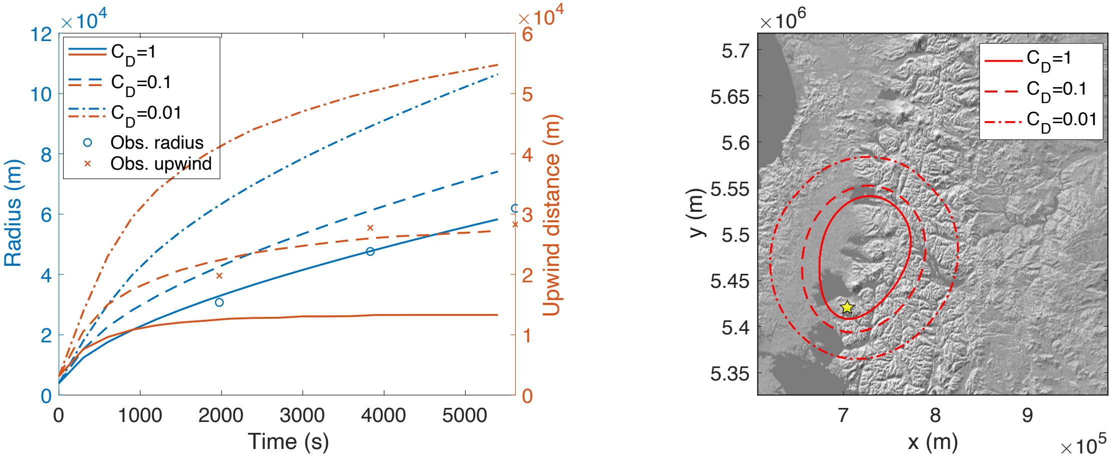
×10^4
12
10
8
6
4
2
0
Radius (m)
×10^4
6
5
4
3
2
1
0
Upwind distance (m)
C_D=1
C_D=0.1
C_D=0.01
Obs. radius
Obs. upwind
0
1000
2000
3000
4000
5000
Time (s)
×10^6
5.7
5.65
5.6
5.55
5.5
5.45
5.4
5.35
y (m)
C_D=1
C_D=0.1
C_D=0.01
7
8
9
x (m)
×10^5

Fig. 1.

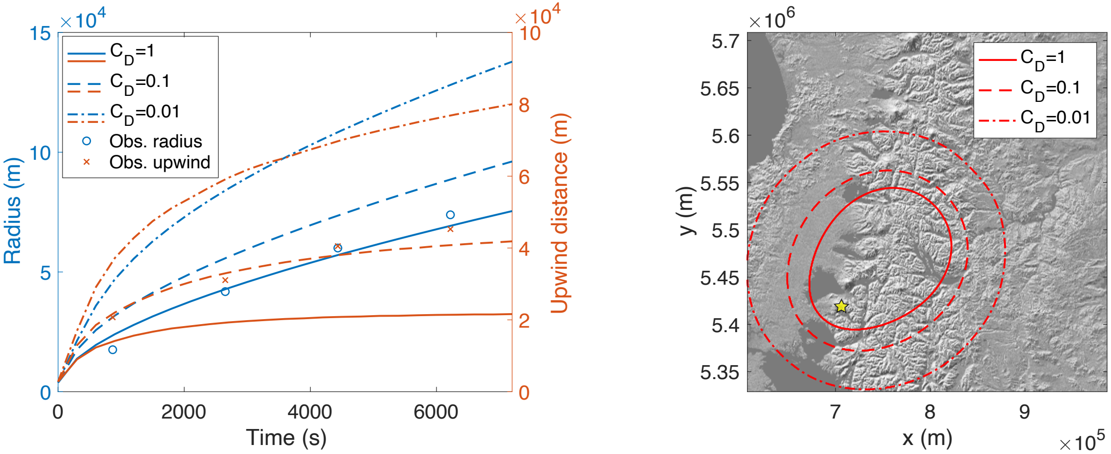
×10⁴
15
10
5
0
Radius (m)
0
2000
4000
6000
Time (s)
×10⁴
10
8
6
4
2
0
Upwind distance (m)
C_D=1
C_D=0.1
C_D=0.01
Obs. radius
Obs. upwind
×10⁶
5.7
5.65
5.6
5.55
5.5
5.45
5.4
5.35
y (m)
7
8
9
x (m)
×10⁵
C_D=1
C_D=0.1
C_D=0.01

Fig. 2.