Exploding super-eruptions can erupt up to thousands of km$^3$ of magma with extremely high mass flow rates (MFR). The plume dynamics of these super-eruptions are still poorly understood. To understand the processes operating in these plumes we used a fluid-dynamical model to simulate what happens at a range of MFR, from values generating intense Plinian columns, as did the 1991 Pinatubo eruption, to upper end-members resulting in co-ignimbrite plumes like Toba super-eruption. Here, we show that simple extrapolations of integral models for Plinian columns to those of super-eruption plumes are not valid and their dynamics diverge from current ideas of how volcanic plumes operate. The different regimes of air entrainment lead to different shaped plumes. For the upper end-members can generate local up-lifts above the main plume (over-plumes). These over-plumes can extend up to the mesosphere. Injecting volatiles into such heights would amplify their impact on Earth climate and ecosystems.
Explosive super-eruptions eject from several hundreds to thousands of km³ of magma at extremely high flow rates¹. Many of these eruptions have had significant impacts to the climate and ecosystems²–⁵. Explosive super-eruptions cover areas within hundreds km from the vent with thick pyroclastic flows, blanket continent-size regions with ash, and inject large quantities of aerosols into the atmosphere⁶. Volatiles injected into the stratosphere can alter the Earth climate on a global scale even causing a volcanic winter that can persist for years to decades²–⁴. On the other hand, tephra layers associated with these catastrophic events are invaluable chronological markers across the affected regions⁶. The mass erupted during super-eruptions is orders of magnitude larger than the biggest eruptions experienced in historic times⁴,⁶–¹⁰. Estimates of mass flow rates (MFRs) during these super-eruptions, obtained from different independent approaches, suggest that they are extremely high, ranging from 10⁹ to 10¹⁴ kg/s⁶,⁸,¹⁰–¹². Such large MFRs require multiple vents or continuous emission along dykes¹³,¹⁴.

Plume dynamics of explosive super-eruptions are not well understood as such large events have not been witnessed. In order to understand how such volumes of material are ejected and dispersed we rely on field evidence and models that can produce the observed deposits. Our current understanding on how plumes of explosive super-eruptions behave is from extrapolations of simple integral models developed for describing columns generated from small MFR. These simple models⁵–¹⁰ are based on the Buoyant Plume Theory (BPT) but the similarity assumption behind has been shown not to be valid for large MFRs¹⁸.

Large explosive eruptions produce Plinian columns when the erupted mixtures of fragmented hot magma and gas entrain air, which heats up and expands making the plume buoyant. Above a critical MFR the eruption column becomes unstable¹⁹ and collapses, producing pyroclastic flows that spreads laterally on the ground. At high MFR, the dilute parts of the hot pyroclastic flows can also become buoyant as they also entrain air, forming a co-ignimbrite eruption plume that can rise up to the stratosphere carrying massive quantities of edulated fine ash and volatiles.

Results

Fluid-dynamical regimes of eruptive plumes for large MFRs.

Here, in order to avoid making unrealistic assumptions, we investigate the plume dynamics using a three-dimensional computational fluid-dynamical code (see Methods) designed to describe the evolution of volcanic plumes and umbrella clouds¹⁹. The code simulates the injection of a well-coupled mixture of solid pyroclasts (ash) and volcanic gas (assumed to be water vapour) from vents of different shapes above a flat surface into a stratified atmosphere. The model does not consider particle sedimentation and particle decoupling²⁰ but captures the plume dynamics (see Methods). In this study we will not consider the effects of the rotation of the Earth on the plume dynamics, which can be very significant for very large eruptions, affecting, among other things, their spreading and shape of the plume²¹,²². For this reason and the sake of simplicity, here we focus on eruptions occurring in the equatorial belt, where these effects are negligible²¹,²² and consider tropical windless atmospheric conditions only (see Methods).

Considering the input parameters reported in Table 1 and atmospheric properties described in Methods, we explored the effects of variable MFRs for different vent geometries, such as a single circular vent, fissure, and vents at different distances. For the sake of simplicity, we focus on the results from a circular vent but these are rather general.

The fluid dynamics of large Plinian columns fed by a MFR ~10⁹ kg/s have been described in several studies⁹,²³,²⁴. In these columns, the fountain-like structure (radially suspended flow²⁴,²⁵) generated in the lower part of the column is characterised by a high-concentration of erupted mixture and it is denser than the ambient air. In this region, the erupted mixture mixes with the air in large-scale vortexes and this mixture becomes rapidly buoyant (see Fig. 1a and Supplementary Movie 1). Approaching the critical MFR at ~10¹⁰ kg/s (see Methods), the radially suspended flow²⁴,²⁵ becomes unstable producing partial collapses, but the main plume still survives. The lower central part of the plume is a Negatively Buoyant Region (NBR), while the area around it is fed with relatively pure air that maintains its buoyancy and efficiently transports the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). The highest velocity remains in the central region generating a mushroom shape plume, with very high mass fractions in the central part up to the top of the plume (see Fig. 1b and Supplementary Movie 2).

Increasing MFR up to 10¹¹ kg/s produces a total collapse of the radially suspended flow, which generates continuous fountaining to the ground, feeding pyroclastic density currents and increasing the radius of the hotter NBR, resulting in a basal region (~60 km diameter) from where the large co-ignimbrite plume will develop (see Fig. 1c). In this case, because of the vigorous rising velocities in the periphery owing to the more effective local air entrainment, the upper central portion of such a large plume has a relatively low mass fraction compared with the outer region (Fig. 1c and Supplementary Movie 3). The resulting plume still maintains a mushroom shape but the plume top has flat, rather than umbonate, cap (Fig. 1c and Supplementary Movie 3).

A further increase of MFR up to 10¹² kg/s will produce a larger co-ignimbrite plume (>150 km in diameter). In this case, the vortices entrain air mainly at the periphery of the co-ignimbrite plume, without affecting the area around the hotter NBR (Fig. 1d and Supplementary Movies 4 and 5). This allows the periphery region of the co-ignimbrite plume to become much more buoyant and increase its velocity. Because of mass conservation, the vertical velocity in the inner part of the plume decreases. This regime results in the formation of a sort of toroid umbrella (donut-like shape), giving to the plume a depressed-cap mushroom shape (i.e., two separate lobes in a 2D cross-section).

Our simulations show that vent geometry has a strong control on the dynamics and stability of the Plinian columns but once co-ignimbrite plumes are generated the processes are predominantly controlled by the diameter of the co-ignimbrite plume, which is typically larger that the vent area, i.e., longer than the fissures or the distance between multiple vents (Supplementary Movies 1–6).

For these reasons, the described features apply to all vent geometries despite the fact that a circular vent was used for the simulations (see Supplementary Movie 6).

Implications for the assessment of eruption parameters. MFRs are typically estimated from the total plume heights assuming BPT is valid. A similar approach has been extended to co-

---

Table 1 Common input parameters and constants used for the three-dimensional simulations

| Variable | Value |
|----------|-------|
| Exit velocity | 256 m/s |
| Exit temperature | 1053 K |
| Exit water fraction | 0.06 |
| Exit density | 3.5 kg/m³ |
| Gas constant of volcanic gas | 462 J/kg/K |
| Gas constant of atmospheric air | 287 J/kg/K |
| Specific heat of solid pyroclasts | 1100 J/kg/K |
| Specific heat of volcanic gas at constant volume | 1348 J/kg/K |
| Specific heat of air at constant volume | 717 J/kg/K |
| Gravity body force | 9.81 m/s² |

---

NATURE COMMUNICATIONS | DOI: 10.1038/s41467-018-02901-0
ignimbrite plume and is still largely used in the volcanological community. However, the dynamics of large co-ignimbrite plumes are markedly different from BPT as their horizontal extension is typically much larger than their height. The simulations indicate that, above a critical MFR, the co-ignimbrite plume rises from a source with radius $R_{CI}$, increasing with MFR as $R_{CI} \propto \sqrt{MFR}$ (with the co-ignimbrite plume radius, $R_{CI}$, expressed in km and MFR in kg/s, see Fig. 2); this power-law dependence of the MFR with run-out distance was predicted in simple models of pyroclastic flows. The mechanisms of air entrainment from such broad sources are profoundly different from, and invalidate the similarity assumption used in, BPT. The difference in the scale of the horizontal extension of plume also affects the behaviour of the upper part of the plume, including the column height and the dynamics in the umbrella cloud.

**Fig. 1** Simulation results for the plumes with different MFRs. a $10^9$ kg/s, b $10^{9.5}$ kg/s, c $10^{10}$ kg/s, d $10^{11}$ kg/s. The figures show snapshots at $t = 800$ s after the eruption initiation: vertical cross-sections of the mass fraction of the erupted mixture is 0.01 (a-d, upper panels); density difference relative to the atmospheric density (a-d, middle panels); three-dimensional isosurface where the mass fraction of the erupted mixture is 0.01 (a-d, lower panels).
The maximum column height and highest mass fraction in the umbrella region is reached for MFR around the critical value, i.e., $10^{10.5}$ kg/s. Remarkably, the Neutral Buoyancy Level (NBL) remains at $\sim$20 km for all the simulations with MFRs above the critical MFR (see Table 2).

For MFR of $\sim10^{11}$ kg/s, maximum plume height is in the peripheral region rather than in the centre, owing to the more efficient entrainment of air from the border of the plume. The maximum height for the bulk mass is at $\sim$50 km but local up-lifts, having a diameter of $\sim$30–40 km, develop above the umbrella region (see Supplementary Figure 1) and keep rising up to the mesosphere ($60–70$ km). In this case, two different effective heights should be considered, one for the bulk mass spreading around the umbrella region and one for the maximum height reached by the local up-lifts (we call them “local over-plume” hereafter). These local over-plumes develop from the base of the periphery of the co-ignimbrite plumes, because of local heterogeneities in the efficiency of air entrainment, and are characterised by higher velocities and larger mass fractions (see Supplementary Figure 1).

The complex relationship between plume height and MFR in Fig. 3 suggests that for large eruption intensities (MFR $>10^9$ kg/s) we cannot use column height estimations to assess the value of MFR$^{15,27}$. To compare our results from the three-dimensional simulations with those of the simple BPT integral models$^{15,27}$, we estimated the main mean variables$^{26}$, such as mixture density difference, $\Delta \rho$, vertical velocity, $U$, temperature, $T$, and mass fraction $\xi$ (see Supplementary Figure 2) and extracted optimal parameter values (see Fig. 3 and Table 3). These BPT models do not adequately describe co-ignimbrite plumes but if they are used as extrapolations the effective entrainment coefficient, $\xi$, should be properly tuned and not assumed as an invariant. Since variations of $H_{\text{NBL}}$ with MFR from sustained Plinian column to fully co-ignimbrite plume are almost negligible ($H_{\text{NBL}} \sim 15–20$ km, see Table 2), accordingly to BPT, this implies that the effective entrainment coefficient should increase with MFR and have significantly different values for the two regimes.

Here, we focus on the dependence of maximum plume height with MFR (Fig. 3 and Fig. 4 for the dynamics of umbrella cloud). The result shows that from $10^9$ to $10^{10}$ kg/s the maximum plume heights remain similar and are between 40 and 60 km. Co-ignimbrite plumes appear steadier than Plinian columns, which show a more oscillatory behaviour (see Supplementary Movies 1–5).
YTT, on the Earth
This has important implications for the effects of eruptions, like n dynamics of super-eruptions. For the most extreme MFRs\(^{13}\), \(\approx 10^{11}\) Discussion integral models to capture such complex plume dynamics.

\[ \xi = \frac{C_0}{H} \]

\[ \text{Mean } \xi \text{ in the umbrella} \]

\[ 10^{9} \]

\[ 10^{9.5} \]

\[ 10^{10} \]

\[ 10^{10.5} \]

\[ 10^{11} \]

\[ H_{\text{NBL}} \text{ (km)} \]

\[ 12-19 \]

\[ 19-23 \]

\[ 15-18 \]

\[ 16-20 \]

\[ 18-21 \]

\[ H_{\text{NBL}} \text{ (km)} \]

\[ 23 \]

\[ 25 \]

\[ 22 \]

\[ 26 \]

\[ 29 \]

\[ H_{\text{N}} \text{ (km)} \]

\[ 40-45 \]

\[ 50-60 \]

\[ 40 \]

\[ 50-60 \]

\[ 60-70 \]

\[ \text{Mean } \xi \text{ in the umbrella} \]

\[ \text{Low} \]

\[ \text{Very high} \]

\[ \text{Medium} \]

\[ \text{High} \]

\[ \text{Very high} \]

\[ {a} \] The lower value corresponds to the column region, while the upper value to the entire umbrella region

\[ {b} \] The radial maximum spreading level was estimated as the height containing the greatest mass of airborne particles\(^4\)

\[ {c} \] The lower value corresponds to dilute part of the plume (\(\xi = 10^{-5}\)), while the upper value to the concentrated part of the plume (\(\xi = 10^{-3}\)).

\[ \text{Plume dynamics} \]

\[ \text{MFR (kg/s)} \]

\[ 10^{9} \]

\[ 10^{9.5} \]

\[ 10^{10} \]

\[ 10^{10.5} \]

\[ 10^{11} \]

\[ \text{Exit temperature (K)} \]

\[ 1053 \]

\[ 1053 \]

\[ 858 \]

\[ 858 \]

\[ 858 \]

\[ \text{Plume radius (km)} \]

\[ 0.60 \]

\[ 1.06 \]

\[ 28.0 \]

\[ 50.0 \]

\[ 85.8 \]

\[ \text{Plume dynamics MFR (kg/s)} \]

\[ \text{Methods} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Table 2 Typical plume heights for different MFRs} \]

\[ \text{Table 3 Input parameters for BPT model inferred from three-dimensional simulations} \]

\[ \text{Discussion} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Table 2 Typical plume heights for different MFRs} \]

\[ \text{Table 3 Input parameters for BPT model inferred from three-dimensional simulations} \]

\[ \text{Discussion} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Discussion} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Discussion} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]

\[ \text{Discussion} \]

\[ \text{Our simulations also show that partially collapsing plumes, generated slightly above the critical MFR value, can reach heights of up to } 50-60 \text{ km and efficiently transport the mixture up to the stratosphere (see Fig. 1b and Supplementary Movie 2). This results in effective upward transport of a large mass fraction of fine ash that is generated from the pyroclastic flows, enriching the fine ash content of the umbrella cloud with respect to the ground-hugging pyroclastic flows. This can be the case for eruptions similar to the Campanian Ignimbrite event for which a MFR of } \approx 10^{9} \text{ kg/s was empirically estimated for the initial Plinian phase and } \approx 2-5 \times 10^{9} \text{ kg/s for the co-ignimbrite phase}^{22,29}. \]
can lead to different critical conditions between the flow regimes described in the main text. However, the qualitative features of each flow regime would be same in the possible ranges of magmatic temperature and water content for magmatic eruptions. We also assumed the equilibrium of pressure and the supersonic flow as the conditions at the vent. The disequilibrium and sub/supersonic flow can change the flow structures near the vent, which results in the change of the final distance of PDC and so, the change of transition between the flow regimes. In addition, we ignore the non-equilibrium effects between the volcanic ash and gas phases. However, the non-equilibrium effects are less relevant in the strong eruptions rather than in the weak eruptions.

Data availability. The authors declare that all data supporting the findings of this study are available in the article and in Supplementary Information. Additional information is available from the corresponding author upon request.

Received: 29 July 2017 Accepted: 8 January 2018
Published online: 13 February 2018

References
1. Self, S. The effects and consequences of very large explosive volcanic eruptions. Philos. Trans. R. Soc. A. 364, 2073–2097 (2006).
2. Robock, A. et al. Did the Toba volcanic eruption of ~74 ka B.P. produce widespread glaciation? J. Geophys. Res. 114, D11077 (2009).
3. Timmreck, C. et al. Climate response to the Toba super-eruption: regional changes. Quat. Int. 258, 30–44 (2012).
4. Costa, A., Smith, V., Macedonio, G. & Matthews, N. The magnitude and impact of the Youngest Toba Tuff super-eruption. Front. Earth Sci. 2, 16 (2014).
5. Blum, B. A., Neri, T. & Manga, M. Campanian Ignimbrite volcanism, climate, and the final decline of the Neanderthals. Geology 43, 411–415 (2015).
6. Lowe, J. J. et al. Volcanic ash layers illuminate the resilience of Neanderthals and early modern humans to natural hazards. Proc. Natl. Acad. Sci. USA 109, 13532–13537 (2012).
7. Smith, V. C., Isia, R., Engwell, S. & Albert, P. G. Tephra dispersal during the Campanian Ignimbrite (Italy) eruption implications for ultra-distal ash transport during the large caldera-forming eruption. Bull. Volcanol. 78, 45 (2016).
8. Wilson, C. J. N. & Hildreth, W. The Bishop Tuff: new insights from eruptive stratigraphy. J. Geol. 105, 407–439 (1997).
9. Martin, M. G., Van Eaton A. R. & Lowenstern J. B., Modeling ash fall distribution from a Yellowstone supereruption. Geochim. Geophys. Geosyst. 15, 3459–3475 (2014).
10. Roche, O., Buesch, D. C. & Valentine, G. A. Slow-moving and far-travelled dense pyroclastic flows during the Peach Spring super-eruption. Nat. Commun. 7, 10890 (2016).
11. Wilson, C. J. N. & Walker, G. P. L. in Tephra Studies, Proceedings of the NATO Advanced Study Institutes Series, vol. 75 (eds Self, S. & Sparks, R. S. J.) 441–448 (Springer, Dordrecht, 1981).
12. Marti, A., Folch, A., Costa, A. & Engwell, A. Reconstructing the plinian and co-ignimbrite sources of large volcanic eruptions: a novel approach for the Campanian Ignimbrite. Sci. Rep. 6, 21220 (2016).
13. Costa, A. & Marti, J. Stress field control during large caldera-forming eruptions. Front. Earth Sci. 4, 92 (2016).
14. Costa, A., Gottsmann, J., Mélön, O. & Sparks, R. S. J. A stress-controlled mechanism for the intensity of very large magnitude explosive eruptions. Earth. Planet. Sci. Lett. 310, 161–166 (2011).
15. Woods, A. W. & Wohletz, K. The dimensions and dynamics of coignimbrite eruption columns. Nature 350, 225–227 (1991).
16. Engwell, S. L., de Michieli Vitturi, M., Esposti Ongaro, T. & Neri, A. Insights into the formation and dynamics of coignimbrite plumes from one-dimensional models. J. Geophys. Res. 121, 4211–4231 (2016).
17. Jessop, D. E., Gilchrist, J., Jellinek, A. M. & Roche, O. Are eruptions from linear fissures and caldera ring dykes more likely to produce pyroclastic flows? Earth. Planet. Sci. Lett. 454, 142–153 (2016).
18. Costa, A. et al. Results of the eruption column model inter-comparison study. J. Volcanol. Geothem. Res. 326, 2–25 (2016).
19. Suzuki, Y. J., Koyaguchi, T., Ogawa, M. & Hachisu, I. A numerical study of turbulent mixing in eruption clouds using a three-dimensional fluid dynamics model. J. Geophys. Res. 110, B08201 (2005).
20. Cerminara, M., Esposti Ongaro, T. & Neri, A. Large eddy simulation of gas–particle kinematic decoupling and turbulent entrainment in volcanic plumes. J. Volcanol. Geothem. Res. 326, 143–171 (2016).
21. Barnes, P. G. & Sparks, R. S. J. Dynamics of giant volcanic ash clouds from super-volcanic eruptions. Geophys. Res. Lett. 32, L24808 (2005).
22. Baines, P. G., Jones, M. T. & Sparks, R. S. J. The variation of large–magnitude volcanic ash cloud formation with source latitude. J. Geophys. Res. 113, D21204 (2008).
23. Suzuki, Y. J. & Koyaguchi, T. A three-dimensional numerical simulation of spreading umbrella clouds. J. Geophys. Res. 114, B03209 (2009).
24. Neri, A. & Dobran, P. Influence of eruption parameters on the thermodynamic dynamics of collapsing volcanic columns. J. Geophys. Res. 99, 11833–11857 (1994).
25. Suzuki, Y. J., Costa, A. & Koyaguchi, T. On the relationship between eruption intensity and volcanic plume height: insights from three-dimensional numerical simulations. J. Volcanol. Geothem. Res. 326, 120–126 (2016).
26. Baines, P. G. & Wohletz, K. The dynamics and thermodynamics of large ash flows. Bull. Volcanol. 58, 175–193 (1996).
27. Sparks, R. S. J. The dimensions and dynamics of volcanic eruption columns. Bull. Volcanol. 48, 3–15 (1986).
28. Rampino, M. R. & Self, S. Volcanic winter and accelerated glacia- tion following the Toba super-eruption. Nature 359, 50–52 (1992).
29. Costa, A. et al. Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption. Geophys. Res. Lett. 39, L10310 (2012).
30. Roe, P. L. Approximate Riemann solvers, parameter vectors, and difference schemes. J. Comput. Phys. 43, 357–372 (1981).
31. van Leer, B. Towards the ultimate conservative difference scheme III. Upstream-centered difference schemes for ideal compressible flow. J. Comput. Phys. 23, 263–277 (1977).
32. Ogden, D., Glatzmaier, G. A. & Wohletz, K. H. Effects of vent overpressure on buoyant eruption columns: implications for plume stability. Earth Planet. Sci. Lett. 268, 283–292 (2008).
33. Carcano, S., Bonaventura, L., Esposti Ongaro, T. & Neri, A. A semi-implicit, second-order-accurate numerical model for multiphase underexpanded volcanic jets. Geosci. Model. Dev. 6, 1905–1924 (2013).
34. Suzuki, Y. J. et al. Inter-comparison of three-dimensional models of volcanic plumes. J. Volcanol. Geothem. Res. 326, 26–42 (2016b).
35. Woods, A. & Kienle, J. The dynamics and thermodynamics of volcanic clouds: theory and observations from the April 15 and April 21, 1990 eruptions of Redoubt Volcano, Alaska. J. Volcanol. Geothem. Res. 62, 273–299 (1994).
36. Costa, A., Folch, A. & Macedonio, G. Density-driven transport in the umbrella region of volcanic clouds: implications for tephra dispersion models. Geophys. Res. Lett. 40, 4823–4827 (2013).

Acknowledgements
A.C. was partially supported by a grant of the International Research Promotion Office, Disaster Management Research Unit, University of Tokyo. Y.I.S and T.K. were partially supported by KAKENHI (grand nos. 25750142 and 17K01323). We warmly thank V.C. Smith for reviewing the English and very helpful suggestions.

Author contributions
A.C. and Y.I.S. designed the simulation set. Y.I.S. performed the runs and processed the results. A.C., Y.I.S., and T.K. interpreted and the results. A.C. wrote the manuscript with input from all the co-authors.

Additional information
Supplementary Information accompanies this paper at https://doi.org/10.1038/s41467-018-02901-0.

Competing interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.