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Thomas Aubry, A. Mark Jellinek, Guillaume Carazzo, Rose Gallo, Kim Hatcher, et al.. A new analytical scaling for turbulent wind-bent plumes: Comparison of scaling laws with analog experiments and a new database of eruptive conditions for predicting the height of volcanic plumes. *Journal of Volcanology and Geothermal Research*, 2017, 343, pp.233-251. <10.1016/j.jvolgeores.2017.07.006>. <insu-02920481>

HAL Id: insu-02920481

<https://insu.hal.science/insu-02920481v1>

Submitted on 15 Jul 2025

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A new analytical scaling for turbulent wind-bent plumes: Comparison of scaling laws with analog experiments and a new database of eruptive conditions for predicting the height of volcanic plumes

Thomas J. Aubry^a, A. Mark Jellinek^a, Guillaume Carazzo^b, Rose Gallo^a, Kim Hatcher^a, Jack Dunning^{a,c}

^a*Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada.*

^b*Observatoire Volcanologique et Sismologique de Martinique, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, CNRS, Morne des Cadets, F-97250 Fonds St Denis, Martinique, France.*

^c*Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ*

Abstract

Various scaling relationships relate the height of volcanic plumes to eruptive source conditions, atmospheric density stratification, turbulent entrainment, and wind stresses. However, observational, analog, and numerical studies used to test these scalings capture only a narrow range of natural eruptive conditions. In particular, existing analytical scalings are not appropriate for the wind stress conditions typical of the majority of volcanic eruptions. Accordingly, we develop a new analytical scaling for the height of buoyant plumes rising in density-stratified uniform crossflows. We compare this scaling to existing analytical scalings (Morton et al. (1956), Hewett et al. (1971)) as well as “functional” scalings (i.e., parameterizations expressed as a function of the Morton et al. (1956) scaling and a regime parameter related to wind stress, Degruyter and Bonadonna (2012), Woodhouse et al. (2013), Carazzo et al. (2014)) using the extensive experimental dataset from Carazzo et al. (2014) along with natural events from a new database including 94 eruptive phases. Our proposed scaling best predicts the height of experimental plumes, which enables us to constrain the ratio of the wind to radial entrainment coefficients. For natural eruptions, the Woodhouse et al. (2013) and Carazzo et al. (2014) scalings,

which account explicitly for wind gradient, best predicts plume heights. We show that accounting for atmospheric stratification and wind improves empirical relationships between mass eruption rates and plume heights. For tested scalings, analysis of residual heights for natural eruption supports the hypothesis that volcanic plumes rise higher in a wetter atmosphere. Finally, for analog plumes rising under moderate to high wind stresses, we show that plume shapes evolve over the plume height, violating the self-similarity assumption on which all scalings and integral model results rely. We discuss consequences for relaxing the self-similarity hypothesis as well as potential improvements for standard integral plume models, in turn.

Keywords: Explosive eruption, Scaling, Entrainment, Volcanic plume height, Eruptive parameters database, Wind

1. Introduction

1.1. Overview: volcanic plume height and the problem of wind stresses

Analytical scaling relationships provide important insight into the dynamics of volcanic plumes by relating the plume heights to (i) eruption source conditions, (ii) atmospheric conditions and (iii) the rate of turbulent entrainment of air into rising plumes. Scalings enable a better understanding of the main controls on plume height which, in turn, enables rigorous assessments of societal impacts of explosive eruptions related to, e.g., falling ash (e.g. Carey and Sparks (1986)), climate change on timescales of weeks to centuries (e.g. Robock (2000); Timmreck (2012)), and the delivery of nutrients to oceans, such as iron (e.g. Langmann et al. (2010); Browning et al. (2015)). Furthermore, when tested against analog laboratory experiments, analytical scalings enable the calibration of turbulent entrainment rates (e.g. Morton et al. (1956); Hoult and Weil (1972); Fischer et al. (1979)) which must be specified in more sophisticated plume models (e.g. Degruyter and Bonadonna (2012); Woodhouse et al. (2013)).

17 A number of recent eruptions strongly impacted by winds (e.g. Eyjafjal-
 18 lajökull in 2010, Cordón Caulle in 2011, Calbuco in 2015) have reanimated
 19 debates over how best to parameterize wind effects on turbulent entrainment
 20 in buoyant plume models, from which scalings are derived (e.g., Degruyter and
 21 Bonadonna (2012); Woodhouse et al. (2013); Mastin (2014); Bonadonna et al.
 22 (2015c); Woodhouse et al. (2015); Girault et al. (2016); Folch et al. (2016)).
 23 Accordingly, a practical aim is to provide a self-consistent intercomparison of
 24 scalings relating the height of volcanic plumes to wind stresses through their
 25 effect on entrainment, as determined from both laboratory experiments and
 26 observations of natural eruptions.

27 1.2. *Plume rising in quiescent conditions: the Morton et al. (1956) scaling*

28 Most scalings for the rise of volcanic plumes follow the classical approach of
 29 Morton et al. (1956). For a fully developed turbulent and incompressible plume
 30 with steady source conditions, Morton et al. (1956) develop a similarity theory
 31 by making the following assumptions:

- 32 1. The turbulent entrainment of ambient air into the plume is driven by
 33 lateral pressure gradients related to velocity differences between the plume
 34 and the atmosphere. Consequently, the inflow velocity u_ϵ of ambient fluid
 35 into the plume is assumed to be proportional to the centerline velocity u
 36 of the plume at a height z such that

$$u_\epsilon = \alpha u \quad , \quad (1)$$

37 where α is the radial entrainment coefficient.

- 38 2. The profiles of velocity and density across the plume are of similar form
 39 at all heights along the plume centerline (e.g., “top-hat” or gaussian func-
 40 tions).

41 For a dry, quiescent and linearly stratified atmosphere, and under the Boussi-
 42 nesq assumption, a plume rising from a point source of buoyancy flux with top-
 43 hat velocity and density profiles will ascend to a maximum height (Figure 1,

left) given by:

$$H^{MTT} = 2.8 \times (2^{-\frac{5}{8}} \pi^{-\frac{1}{4}} \alpha^{-\frac{1}{2}} F_0^{\frac{1}{4}} N^{-\frac{3}{4}}) \quad , \quad (2)$$

where the prefactor 2.8 is the non-dimensional maximum plume height, F_0 is the source buoyancy flux of the plume, $N = \sqrt{-\frac{g}{\rho_{a0}} \frac{d\rho_a}{dz}}$ is the atmospheric Brunt-Väisälä frequency with g the Earth's gravity acceleration, ρ_a the ambient density, z the altitude, and 0 subscript denoting properties taken at source altitude (cf Table 1 for a summary of symbols used). Equation 2 is, thus, an analytical expression that explicitly relates the height of a plume to its source condition, the environmental stratification and the radial entrainment rate.

Explosive volcanic plumes erupt as negatively buoyant jets with dense pyroclasts in the flow. The initial momentum flux drives entrainment of atmosphere, which is heated by hot pyroclasts, in turn reducing the mean density of the jet. If the efficiency of turbulent entrainment and heating from pyroclasts is sufficiently high, the buoyancy of the column reverses before the initial momentum flux is exhausted and the mixture rises by natural convection. The height of the momentum-dominated region is generally small compared to the total rise height, so that Equation 2 is commonly applied to study the rise of volcanic plumes, where the buoyancy flux is specified in terms of an enthalpy flux (Wilson et al., 1978; Woods, 1995).

The radial entrainment coefficient α is historically calibrated using small-scale laboratory experiments (e.g. Morton et al. (1956); Fischer et al. (1979); Chen and Rodi (1980); Kaminski et al. (2005)), large-scale experiments (e.g. Dellino et al. (2014)), or numerical simulations (e.g. Suzuki and Koyaguchi (2010, 2015)). Laboratory experiments show that for radial top-hat-shaped profiles, α lies between 0.065 and 0.07 in pure jets (driven by a source of momentum only, e.g., Fischer et al. (1979)), and between 0.1 and 0.16 in pure plumes (driven by a source of buoyancy only, e.g., Morton et al. (1956); George et al. (1977)). Kaminski et al. (2005), however, show that instead of being constant, α is a function of the shapes of the velocity, density and turbulent shear stress profiles, and of the vertically varying (i.e., "local") Richardson number,

73 which expresses the ratio of the the momentum and buoyancy fluxes:

$$\mathcal{R}i = \frac{rg'}{u^2} . \quad (3)$$

74 Here, r is the jet radius, $g' = \frac{\rho - \rho_a}{\rho_a} g$ is the reduced gravity of the jet, where ρ is
75 the jet density.

76 1.3. Plume rising under windy conditions: the Hewett et al. (1971) scaling

77 Morton et al. (1956) neglect the impact of atmospheric winds, which have
78 long been recognized to strongly affect entrainment mechanics (Hoult et al.,
79 1969; Bursik, 2001). Qualitatively, atmospheric crosswinds bend the plume and
80 decrease the radial gradient of axial (relative to plume axis) velocity between
81 the plume and the atmosphere, but they create a radial gradient of normal
82 velocity (normal to the local plume centerline, see Figure 2). Assuming a linear
83 superposition, both velocity gradients contribute to an entrainment velocity
84 Hoult et al. (1969):

$$u_\epsilon = \alpha|u - w \sin(\phi)| + \beta|w \cos(\phi)| , \quad (4)$$

85 where w is the horizontal wind speed, ϕ is the local deflection of the plume
86 with respect to the vertical (cf Figure 1, center) and β is the wind entrainment
87 parameter.

88 Whether the mechanics of entraining eddies is controlled predominantly by
89 wind or plume velocity gradients is expressed by the local ratio of the wind
90 velocity to the plume velocity:

$$\mathcal{W}^* = \frac{w}{u} . \quad (5)$$

91 Laboratory experiments (e.g. Hoult and Weil (1972); Huq (1997); Contini et al.
92 (2011)), field observations (e.g. Hoult et al. (1969); Briggs (1972)) and numerical
93 studies (e.g. Suzuki and Koyaguchi (2015)) suggest that β lies between 0.1
94 and 1. Most studies assume that β is a constant (e.g. Hewett et al. (1971);
95 Degruyter and Bonadonna (2012); Woodhouse et al. (2013); Bonadonna et al.
96 (2015c)). Using the Morton et al. (1956) pure plume model and Equation 4, and

97 assuming a uniform wind of magnitude W such that $\mathcal{W}^* \gg 1$, Hewett et al.
 98 (1971) showed that the maximum plume height is given by (Figure 1, right):

$$H^{HFH} = 6^{\frac{1}{3}} \pi^{-\frac{1}{3}} \beta^{-\frac{2}{3}} F_0^{\frac{1}{3}} N^{-\frac{2}{3}} W^{-\frac{1}{3}} . \quad (6)$$

99 As with Equation 2, this analytical scaling relates the height of a pure plume
 100 to source conditions and stratification, but also to the crossflow speed and the
 101 wind entrainment coefficient (instead of the radial entrainment coefficient for
 102 Equation 2).

103 1.4. Plume rising under arbitrary wind stress: overview of existing "functional" 104 scalings

105 Neither the Morton et al. (1956) ($\mathcal{W}^* = 0$) nor the Hewett et al. (1971)
 106 ($\mathcal{W}^* \gg 1$) assumptions are appropriate for the majority of explosive volcanic
 107 eruptions, which commonly occur under intermediate wind stress conditions,
 108 i.e., $\mathcal{W}^* \simeq 10^{-2} - 1$ (Figure 1 and Carazzo et al. (2014)). Consequently, various
 109 "functional" scalings are commonly applied, which are adjustments to Equa-
 110 tions 2 and 6 using different wind regime parameters. In this study, we will con-
 111 sider the three scalings recently proposed by Degruyter and Bonadonna (2012),
 112 Woodhouse et al. (2013) and Carazzo et al. (2014). These scalings have been
 113 developed specifically for application to the rise of volcanic plumes and enable
 114 predictions where the Morton et al. (1956) and Hewett et al. (1971) scalings are
 115 not applicable, but are not fully analytical.

116 Degruyter and Bonadonna (2012) scale the source buoyancy flux of an erup-
 117 tion as the sum of the buoyancy fluxes obtained from the Morton et al. (1956)
 118 and Hewett et al. (1971) scalings. Rearranging their scaling for the source buoy-
 119 ancy flux (cf Appendix A), the plume height is given by:

$$H^{DB} = H^{MTT} \frac{1 + 0.17 \frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^* + 0.00061 (\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*)^2}{1 + 0.48 \frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^* + 0.0072 (\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*)^2} , \quad (7)$$

120 where the main control parameter is now

$$\mathcal{V}_0^* = \frac{W}{(F_0 N)^{\frac{1}{4}}} , \quad (8)$$

121 where W is the horizontal wind speed averaged over the plume height. Here,
 122 $\mathcal{V}_0^*$ can be interpreted the same way as $\mathcal{W}_0^*$ ($\mathcal{W}^*$ taken at source), but with the
 123 plume velocity being scaled using the source buoyancy flux instead of momentum
 124 flux. This scaling has been tested using 1D integral models and the 1980 Mt St
 125 Helens and 2010 Eyjafjallajökull eruptions, but it has never been tested against
 126 laboratory experiments.

127 For linear wind gradients ($\frac{dw}{dz}$ constant and $w = 0$ at the vent altitude),
 128 Woodhouse et al. (2013) demonstrate that plume height depends only on H^{MTT} ,
 129 the atmospheric gradient Richardson number

$$\mathcal{R}_g^{wind} = \frac{N^2}{(\frac{dw}{dz})^2} \quad , \quad (9)$$

130 and the ratio of the entrainment coefficients $\frac{\beta}{\alpha}$. No analytical solution has
 131 been found for this situation but they show that the numerical solution is well
 132 approximated by:

$$H^{WHPS} = H^{MTT} \frac{1 + (0.87 + 0.05\frac{\beta}{\alpha})(\mathcal{R}_g^{wind})^{\frac{1}{2}}}{1 + (1.09 + 0.32\frac{\beta}{\alpha})(\mathcal{R}_g^{wind})^{\frac{1}{2}} + (0.06 + 0.03\frac{\beta}{\alpha})(\mathcal{R}_g^{wind})} \quad . \quad (10)$$

133 Using a 1D integral model of volcanic plumes, Woodhouse et al. (2013) test
 134 Equation 10 with source and atmospheric conditions corresponding to the Ey-
 135 jafjallajökull 2010 eruptions. They also compare Equation 10 to a larger set of
 136 eruptions (Sparks et al., 1997; Mastin et al., 2009) but use US Standard atmo-
 137 sphere and idealized wind profile instead of the observed atmospheric conditions.
 138 This scaling has not been tested against experimental datasets.

139 More recently, Carazzo et al. (2014) propose a scaling based only on lab-
 140 oratory experiments and a 1D model of turbulent buoyant jet with variable
 141 entrainment (Kaminski et al., 2005). In this treatment, the height reached in a
 142 quiescent environment is corrected using the regime parameter $\mathcal{T}^*$ to account
 143 for wind effects, where

$$\mathcal{T}^* = \left(\frac{H^{MTT}}{U_0}\right)\left(\frac{w(H_{tp})}{H_{tp}}\right) \quad (11)$$

144 expresses the ratio of the wind gradient in the troposphere (where H_{tp} is the
 145 tropopause height) and the vertical velocity gradient in the plume. Simplified

expressions relating mass eruption rates to plume height are proposed by these authors, together with 9 empirical parameters that depend on the eruption latitudes (cf equations 7-10 in Carazzo et al. (2014)). To build a straightforward scaling, we replace the volume flow rate calculated from their 1D model, without wind and with α dependent on the local Richardson number, by the volume flow rate obtained with the Morton et al. (1956) scaling, with a constant α . The resulting expression for the plume height is:

$$H^{CGABK} = H^{MTT} e^{-a_c \mathcal{T}^*} \quad (12)$$

where a_c is an empirical parameter constrained by laboratory experiments. The original Carazzo et al. (2014) scaling has been shown to predict accurately the source conditions of a selection of 10 explosive volcanic eruptions, but as presented in Equation 12 it has not been tested yet.

1.5. Summary and motivation for a new analytical scaling law

Analytical scalings (Equations 2 and 6) give important insights on the physics of volcanic plumes, and can be used to calibrate entrainment coefficients α and β required in 1D models of volcanic plumes by using laboratory experiments. However, these scalings are often not applicable to volcanic plumes because they require either unrealistically low or high wind speeds. On the other hand, functional scalings (Equations 7, 10 and 12) enable predictions where the analytical scalings of Morton et al. (1956) and Hewett et al. (1971) fail. Nonetheless, they have mostly been tested using 1D models of volcanic plumes, and a restricted number of eruptions for which eruption source conditions and heights can be inferred, albeit with large uncertainties. Consequently, their generic predictive power is uncertain. The scalings discussed here also do not provide consistent predictions, even in the windy conditions for which they were designed (Figure 3). In addition, the values of α and β are subject to large uncertainties (0.05 to 0.16 for α and 0.1 to 1 for β). Where they are calibrated, the entrainment parameters α and β are understood over a narrow subset of the full range of wind regimes in which volcanic eruptions commonly occur (Carazzo et al., 2014).

Figure 3 shows, for each scaling, the uncertainty in predicted height associated with uncertainty on entrainment coefficients. The height predicted by a given scaling can vary by almost a factor of 2 depending on the chosen values for α and β . This uncertainty affects not only scalings, but also 1D integral volcanic plume models (e.g. Mastin (2014); Woodhouse et al. (2015)) and is recognized as the key factor to improve volcanic plume models based on entrainment parameterization (e.g. Costa et al. (2016); Devenish (2016); Macedonio et al. (2016)).

To make progress, in Section 2, we develop a new analytical scaling law for buoyant plumes rising in density-stratified, uniform crossflows that is applicable to wind regimes where explosive eruption most commonly occur. To help future studies in making a choice among all existing scalings, we also provide a benchmark comparison of the newly derived scaling with the five scalings introduced in the present section. The scalings are compared using a recent set of laboratory experiments (Carazzo et al., 2014) as well as a new dataset of observations from natural eruptions presented in section 3. In section 4, we compare height predictions from each scaling, using both experimental and natural eruptions datasets. We will show that the newly proposed scaling places new constraints on the entrainment coefficients α and β . We also assess the best empirical relationship to predict mass eruption rates on the basis of the set of parameters used in each scaling. In section 5, we discuss the implication of the new constraint on entrainment coefficients, and the extent to which the use of self-similarity theory is adequate under variable wind conditions. In section 6, we summarize our conclusions.

2. Theory

2.1. Derivation of a new analytical scaling

We build a new scaling for plume height based on the buoyant plume model of Morton et al. (1956) modified by Hoult et al. (1969) to account for wind (Section 1). In particular, we assume that cross-plume velocity and density

203 profiles have a top-hat shape, and that the plume rises into a uniform crossflow
 204 (i.e. $w(z) = W$) in an environment with a linear density stratification with a
 205 strength N . The key assumptions that enable us to develop a new scaling are:
 206 i) the plume deflection relative to the vertical ϕ (Figure 2, top) is small and
 207 ii) the entrainment rate can be approximated by a constant. The strength of
 208 this assumption is that the equations governing the plume rise can be recast in
 209 form to the Morton et al. (1956) equations, where the equivalent entrainment
 210 coefficient ϵ depends on both the radial and wind entrainment coefficients (α
 211 and β) and the regime parameter $\mathcal{W}_0^* = \frac{W}{U_0}$ ($\mathcal{W}^*$ taken at source).

212 Using the control volume defined in Figure 2 (bottom), the plume rise is
 213 governed by the conservation of volume flux $q = \pi r^2 u$, momentum flux $m =$
 214 $\pi r^2 u^2$, and buoyancy flux $f = \pi r^2 u g'$ along the plume centerline. Let z and
 215 x be the vertical and horizontal distances from the source such that they are
 216 related to s , the distance from the source along the plume centerline, and the
 217 local deflection angle ϕ :

$$\sin(\phi) = \frac{dx}{ds} \quad ; \quad \cos(\phi) = \frac{dz}{ds} . \quad (13)$$

218 We note for clarification that most authors (e.g. Bursik (2001)) instead use the
 219 inclination of the plume centerline to the horizontal $\theta = \frac{\pi}{2} - \phi$ to relate s to x
 220 and z .

221 Next, we parametrize the entrainment rate ϵ following Hoult et al. (1969):

$$\epsilon = \frac{u_\epsilon}{u} = \alpha \left| 1 - \frac{Wq}{m} \sin(\phi) \right| + \beta \left| \frac{Wq}{m} \cos(\phi) \right| . \quad (14)$$

222

223 Projected in the $[x, z]$ coordinate system, conservation of volume, x - and z -
 224 momentum, and buoyancy fluxes are (e.g. Hewett et al. (1971); Bursik (2001);

225 Woodhouse et al. (2013)):

$$\frac{dq}{ds} = 2 \pi^{\frac{1}{2}} \epsilon m^{\frac{1}{2}} \quad (15a)$$

$$\frac{dm \sin(\phi)}{ds} = W \frac{dq}{ds} \quad (15b)$$

$$\frac{dm \cos(\phi)}{ds} = \frac{fq}{m} \quad (15c)$$

$$\frac{df}{ds} = -qN^2 \cos(\phi) \quad (15d)$$

226 To build physical insight, we non-dimensionalize equations 13 and 15a-15d
 227 using the following scales (Morton et al., 1956):

$$q = 2^{\frac{5}{8}} \pi^{\frac{1}{4}} F_0^{\frac{3}{4}} N^{-\frac{5}{4}} \hat{q} \quad , \quad m = 2^{\frac{1}{2}} F_0 N^{-1} \hat{m} \quad , \quad f = F_0 \hat{f} \quad , \quad x, z, s = 2^{-\frac{5}{8}} \pi^{-\frac{1}{4}} F_0^{\frac{1}{4}} N^{-\frac{3}{4}} \hat{x}, \hat{z}, \hat{s} \quad , \quad (16)$$

228 where the hats denote dimensionless quantities. Note that the entrainment rate
 229 is not included in this non-dimensionalization and that the prefactors used are
 230 different than those of Morton et al. (1956) because we use top-hat instead
 231 of gaussian profiles. Using Equation 13 and the chain rule, the dimensionless
 232 governing equations become:

$$\cos(\phi) \frac{d\hat{q}}{d\hat{z}} = \epsilon \hat{m}^{\frac{1}{2}} \quad (17a)$$

$$\frac{d\hat{m} \sin(\phi)}{d\hat{z}} = 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \frac{d\hat{q}}{d\hat{z}} \quad (17b)$$

$$\cos(\phi) \frac{d\hat{m} \cos(\phi)}{d\hat{z}} = \frac{1}{2} \frac{\hat{f} \hat{q}}{\hat{m}} \quad (17c)$$

$$\frac{d\hat{f}}{d\hat{z}} = -\hat{q} \quad (17d)$$

233 Equations 17b and 17c can be combined as $2\hat{m} \sin(\phi) \times (17b) + 2\hat{m} \times (17c)$
 234 to give:

$$\cos(\phi) \frac{d\hat{q}}{d\hat{z}} = \epsilon \hat{m}^{\frac{1}{2}} \quad (18a)$$

$$\frac{d\hat{m} \sin(\phi)}{d\hat{z}} = 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \frac{d\hat{q}}{d\hat{z}} \quad (18b)$$

$$\frac{d\hat{m}^2}{d\hat{z}} = \hat{f} \hat{q} + 2^{\frac{9}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \sin(\phi) \hat{m} \frac{d\hat{q}}{d\hat{z}} \quad (18c)$$

$$\frac{d\hat{f}}{d\hat{z}} = -\hat{q} \quad (18d)$$

235 To simplify further Equations 18a-18d, we use a small angle approximation
 236 such that $\phi \ll 1$, and assume that the momentum flux carried by the wind is
 237 smaller than the plume buoyancy flux such that $2^{\frac{9}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* < 1$. To 1st order in
 238 ϕ , the governing equations 18a-18d then become:

$$\frac{d\hat{q}}{d\hat{z}} = \epsilon \hat{m}^{\frac{1}{2}} \quad (19a)$$

$$\frac{d\hat{m} \phi}{d\hat{z}} = 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \frac{d\hat{q}}{d\hat{z}} \quad (19b)$$

$$\frac{d\hat{m}^2}{d\hat{z}} = \hat{f} \hat{q} \quad (19c)$$

$$\frac{d\hat{f}}{d\hat{z}} = -\hat{q} \quad (19d)$$

239 We note that with a constant $\mathcal{V}_0^*$ (uniform wind and linear stratification),
 240 Equation 19b can be written $\frac{d(\hat{m} \phi - 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \hat{q})}{d\hat{z}} = 0$.

241 With initial condition $\hat{m} = \hat{q} = 0$, the small angle approximation thus implies
 242 $\phi = 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \frac{\hat{q}}{\hat{m}} \ll 1$. Equations 19a, 19c and 19d are identical to Equations 11
 243 and 12 in Morton et al. (1956), but with a variable entrainment rate:

$$\epsilon = \alpha \left(1 + \frac{\beta}{\alpha} \left| 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \frac{\hat{q}}{\hat{m}} \right| \right) \quad (20)$$

244 using Equations 20, 16, $\phi \ll 1$, and $2^{\frac{9}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* < 1$. To obtain a system of govern-
 245 ing Equations similar to Morton et al. (1956), we approximate the entrainment
 246 rate with a constant value $\bar{\epsilon}$. From Equation 20, a natural scale for $\bar{\epsilon}$ for pure
 247 plumes is:

$$\bar{\epsilon} \propto \alpha \left(1 + \frac{\beta}{\alpha} 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^* \right) \quad (21)$$

249

250 With source conditions $\hat{f} = 1$, $\hat{m} = \hat{q} = 0$ specified at $\hat{z} = 0$, Equation 19a,
 251 19c and 19d are equivalent to Equations 11 and 12 in Morton et al. (1956) with
 252 the only difference being the radial entrainment rate α replaced by an effective
 253 entrainment rate ϵ defined by Equation 21. Consequently, the maximum plume
 254 height scales as:

$$H_{max} \propto (1 + \frac{\beta}{\alpha} 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{V}_0^*)^{-\frac{1}{2}} H^{MTT} . \quad (22)$$

255

256 Equation 22 scales well with the numerical solution of Equations 15 for $\mathcal{V}_0^* \leq$
 257 $\mathcal{O}(1)$ and $\frac{\beta}{\alpha} \leq 10$ (Figure S1). For buoyant jets where the source momentum
 258 flux is not null, the scale for the wind to plume velocity ratio can be based on
 259 the source momentum flux, i.e., $\mathcal{W}_0^* = \frac{W}{U_0}$ instead of $\mathcal{V}_0^*$ so that Equation 21
 260 becomes:

$$\bar{\epsilon} \propto \alpha (1 + \frac{\beta}{\alpha} 2^{\frac{1}{8}} \pi^{\frac{1}{4}} \mathcal{W}_0^*) \quad , \quad (23)$$

261 and the plume height scales with

$$H^{AJC} = (1 + \frac{\beta}{\alpha} \mathcal{W}_0^*)^{-\frac{1}{2}} H^{MTT} . \quad (24)$$

262 A choice between these two velocity ratios $\mathcal{W}_0^*$ and $\mathcal{V}_0^*$ to scale the entrain-
 263 ment rate $\bar{\epsilon}$ for buoyant jets should be based on the ratio of the jet/plume
 264 transition length $l_m = M_0^{\frac{3}{4}} F_0^{-\frac{1}{2}}$ (where M_0 is the source momentum flux, e.g.
 265 Fischer et al. (1979)) and the buoyant plume height H^{MTT} . The ratio $\frac{l_m}{H^{MTT}}$
 266 varies between 0.1 and 1 for the Carazzo et al. (2014) experiments, with the
 267 same range estimated for natural eruptions. Experiments ultimately show that
 268 $\mathcal{W}_0^* = \frac{W}{U_0}$ is the most appropriate velocity ratio scale for the $\mathcal{W}_0^* - \mathcal{R}i_0$ parameter
 269 space considered (Section 4 and Figure S2).

270 2.2. Discussion of additional assumptions

271 In summary, in developing this correction to the Morton et al. (1956) scaling,
 272 we make four assumptions in addition to those articulated by Morton et al.

273 (1956):

- 274 • *A1*: The plume rises in a uniform wind field of speed W .
- 275 • *A2*: $\phi \ll 1$: the angle of rise is very small
- 276 • *A3*: $\mathcal{V}_0^* < 1$: the momentum flux carried by wind is smaller than the
277 buoyancy flux carried by the plume.
- 278 • *A4*: $\epsilon \simeq \bar{\epsilon}$: the entrainment rate can be approximated by a mean value.
279 We propose that this mean value scales with $\mathcal{V}_0^*$ for pure plumes ($\bar{\epsilon} \propto$
280 $\alpha(1 + \frac{\beta}{\alpha}\mathcal{V}_0^*)$), and with $\mathcal{W}_0^*$ for buoyant jets with low Richardson number
281 ($\bar{\epsilon} \propto \alpha(1 + \frac{\beta}{\alpha}\mathcal{W}_0^*)$).

282 A uniform wind profile (A1) is not generally realistic, and depends in par-
283 ticular on the region and season considered (e.g. Mastin (2014); Aubry et al.
284 (2016)). Although the average wind speed is expected to be the main control on
285 the plume height, the exact shape of the wind profile is also important (Girault
286 et al., 2016). However, it is complex to incorporate these effects into a scaling
287 relationship. Ideal shapes such as uniform wind (e.g., Hewett et al. (1971)) or
288 linear wind gradient (e.g., Woodhouse et al. (2013)) are consequently commonly
289 used.

290 We expect $\phi \ll 1$ (A2) to hold when $\mathcal{V}_0^* \ll 1$ for a pure plume and $\mathcal{W}_0^* \ll 1$
291 for a pure jet. For buoyant jets, measurements of the mean angle of rise $\bar{\phi} =$
292 $\frac{1}{H_{max}} \int_0^{H_{max}} \phi dz$ in the Carazzo et al. (2014) experiments shows that A2 holds
293 when $\mathcal{V}_0^* \leq \mathcal{O}(1)$ (A3) and $\mathcal{W}_0^* \ll 1$ (Figure S3), with A2 and A3 both holding
294 for $\simeq 12$ experiments and being both violated for $\simeq 7$ experiments (out of 27, cf
295 Figure S4). For pure plumes and $\mathcal{V}_0^* \leq 1$, Figure S1 shows that the small angle
296 hypothesis enables good prediction of the maximum plume height.

297 The same figure also comforts that the entrainment rate can be approximated
298 by a constant mean value (A4), scaling with $\mathcal{V}_0^*$ for pure plumes with $\mathcal{V}_0^* \leq$
299 1. Whether the mean entrainment rate scales with $\mathcal{W}_0^*$ for buoyant jets with
300 low Richardson number is more challenging to test directly on the basis of the
301 data used in this paper. However, the performance of the proposed scaling in

302 predicting the height of the Carazzo et al. (2014) experiments (Section 4) also
 303 reflects the validity of assumptions made in deriving this scaling, including A4,
 304 for the regime parameter space used by Carazzo et al. (2014).

305 **3. Data and method**

306 *3.1. Data from laboratory experiments*

307 We use two sets of laboratory experiments presented in detail in Contini et al.
 308 (2011) and Carazzo et al. (2014) . In both sets of experiments, turbulent salt
 309 water plumes are injected at a fixed rate into a tank containing salt water with
 310 a specified linear density gradient. To simulate the effect of wind, the nozzle
 311 through which plumes are injected was translated relative to the tank at a fixed
 312 speed. The evolution of the plume was recorded using a digital video camera
 313 (25 images/s). For each experiment, source and environment parameters were
 314 carefully measured in order to compute the different regime parameters (e.g.
 315 equations 3, 8, 11) and scaling heights (e.g. equations 2, 6, 7, 10, 12 and
 316 24). In addition, the average maximum height H_{max} was measured from the
 317 stack of all images recorded for an experiment as the maximum height where
 318 the tracer concentration becomes indistinguishable from the background. The
 319 duration of an experiment is much longer than the plume rise timescale, so
 320 that transient turbulent features are removed when stacking all images together
 321 (Figure 9). For the Carazzo et al. (2014) dataset, we measure the average tracer
 322 concentration along a series of profiles normal to the centerline with digital
 323 image analysis (Figure S5). The main source parameters and maximum height
 324 of the 27 experiments from Carazzo et al. (2014) are indicated in Table S1.

325 *3.2. Data from explosive eruptions*

326 We extend the database compiled by Mastin (2014) and use 94 eruption
 327 phases for which independent estimates of the erupted mass, the eruption du-
 328 ration, and the average plume height are available. Uncertainties in estimation
 329 of these three parameters can be large and vary a lot among eruptions. Thus,

we also strive to quantify these uncertainties for each eruption. We account for various contributions to these uncertainties such as:

- Erupted mass: the choice of an empirical function used to fit and integrate the square root of isopach/isomass area vs the thickness of the deposit, which can lead to differences of up to a factor 2 on the final erupted mass (e.g. Biass and Bonadonna (2011); Bonadonna et al. (2015a))
- Eruption duration: differences in the interpretation of the timing of deposition of tephra layers as well as the interpretation of the start and end of an eruptive phase, which can be based on seismological, remote sensing or visual observations (e.g. Paladio-Melosantos et al. (1996); Castruccio et al. (2016))
- Plume height: discrepancies between different estimates (e.g. visual, ground-based radar or satellite), differences between the height reached by the tephra plume and the gas plume, and temporal variability in the plume height (e.g. Tupper and Wunderman (2009))

In Appendix B, we detail a well-constrained and poorly constrained case for each of these three parameters, and explain important differences with estimates made by Mastin (2014) for two eruptions.

For each eruptive phase, the average wind speed, vertical shear and Brunt Väisälä frequency are retrieved from the NCEP-NCAR reanalysis (Kalnay et al., 1996) using the same method as Mastin (2014). For the few eruptive phases occurring before 1948, the 20th Century Reanalysis (Compo et al., 2011) is used to retrieve atmospheric parameters. We assumed a relative uncertainty of 10% for all atmospheric parameters because differences between these parameters was small when calculated using different reanalysis or atmospheric soundings, for one high-latitude and one tropical eruptive phase.

The calculation of the regime parameters $\mathcal{W}_0^*$ and $\mathcal{T}^*$ requires an independent estimation of eruptions exit velocity U_0 . We follow Woods and Bower

358 (1995) to compute the exit velocity as:

$$U_0 = 1.85\sqrt{Rn_0T_0} \quad . \quad (25)$$

359 R is the specific gas constant, n_0 the magma volatile content and T_0 the magma
360 temperature. We assume that the water content of melt inclusions is repre-
361 sentative of the gas content at the vent. For the few eruptions for which we
362 were not able to find n_0 in the literature, we assigned $n_0 = 3.5 \pm 3\text{wt.}\%$ (95%
363 confidence level) based on the distribution of n_0 found for the other eruptions.
364 We assume an exit temperature of $T_0 = 1200 \pm 200\text{K}$. Equation 25 assumes
365 that there is a free decompression at the vent exit, which does not apply to all
366 explosive eruptions (e.g., Koyaguchi et al. (2010)). To account for uncertainty
367 related to the use of this scaling for the exit velocity, we assume a 50% relative
368 uncertainty, despite uncertainties on n_0 and T_0 found in the literature would
369 typically result in relative uncertainties of 20 – 40% on the exit velocity, using
370 Equation 25.

371 Table S2 contains the newly compiled database. It is important to stress
372 that these data reflect average eruptive and atmospheric parameters of each
373 eruption phase. Many of the eruptive phases we consider do not have a steady
374 behaviour through their entire duration. However, it is difficult to estimate
375 time-dependent mass eruption rate independently from the plume height for
376 the vast majority of eruptions for which other parameters are well constrained.
377 Although the large number of eruptions in our database and our treatment of
378 uncertainties (Section 3.4) make our results more robust, unsteadiness in source
379 conditions and plume height remain a limitation for the compiled database.

380 *3.3. Dynamical similarity of laboratory experiments*

381 Given large uncertainties in the measurements of erupted mass, eruption du-
382 ration and average eruption heights, analog laboratory experiments are crucial
383 to test the performance of models relating plume height to source conditions.
384 However, to test models in dynamical regimes representative of volcanic erup-
385 tions, it is necessary that experimental studies are performed in the region of

the $\mathcal{R}i_0$ - $\mathcal{W}_0^*$ - $\mathcal{V}_0^*$ parameter space that are appropriate for explosive eruptions. Contrary to previous experimental studies (e.g. Hewett et al. (1971), Hoult and Weil (1972), Huq (1997), Yang and Hwang (2001) or Contini et al. (2011)) Carazzo et al. (2014) data span virtually the full range of $\mathcal{R}i_0$ - $\mathcal{W}_0^*$ - $\mathcal{V}_0^*$ in which explosive eruptions apparently occur (Figure 4 and S3). $\mathcal{W}_0^*$ ranges from $5 \cdot 10^{-3}$ to $5 \cdot 10^{-1}$, $\mathcal{V}_0^*$ from 10^{-2} to 10^1 and $\mathcal{R}i_0$ from 10^{-4} to 10^{-1} , although some explosive eruptions from Table S2 are characterized by larger $\mathcal{R}i_0$ ranging from 10^{-1} to 10^0 .

Qualitatively, the plume style (defined hereafter) has similar transitions for experiments and eruptions, which further corroborates that the analog experiments capture the basic mechanics of natural explosive eruptions. For $\mathcal{R}i_0^{wind} = \frac{\mathcal{R}i_0}{\mathcal{W}_0^{*2}} > 5$, most natural and experimental plumes are characterized by an umbrella spreading both upwind and downwind (strong plumes). On the other hand, for $\mathcal{R}i_0^{wind} < 0.5$, most plumes do not rise above their neutral buoyancy level and only spread downwind (weak plumes). Distorted plumes rise above their neutral buoyancy level but spread downwind only, and mostly correspond to $0.5 < \mathcal{R}i_0^{wind} < 5$ for natural and experimental plumes. Given large uncertainties in eruption source parameters, as well as in attributing a plume style to an eruption from a few photographs, the uncertainty on critical $\mathcal{R}i_0^{wind}$ values at which the plume transition are likely of half an order of magnitude.

In contrast, the Contini et al. (2011) dataset spans only two narrow regions of the $\mathcal{R}i_0$ - $\mathcal{W}_0^*$ space (Figure 4). Consequently, we will restrict our comparison of scalings to the Carazzo et al. (2014) experiments along with eruptive parameter database. We will discuss results obtained when using the Contini et al. (2011) data in Section 5.

3.4. Method

A major aim of this study is to compare the performance of our proposed scaling (Equation 24) with the performances of published scalings (Equations 2, 6, 7 10 and 12) for predicting the height of explosive volcanic eruptions from source and atmospheric conditions. Our goal is, in part, to provide a

416 benchmark comparison of scalings for volcanic plumes. To this end, we fit
 417 the plume height predicted by each scaling to the observed plume height, and
 418 compare model fits and coefficient of determination R^2 . For the Morton et al.
 419 (1956) and Hewett et al. (1971) scalings, we use a linear fit. For the Degruyter
 420 and Bonadonna (2012), Woodhouse et al. (2013), Carazzo et al. (2014) and our
 421 proposed scaling, there is an additional fitting parameter, which is related to
 422 the ratio of entrainment coefficients for the Degruyter and Bonadonna (2012),
 423 Woodhouse et al. (2013) and our proposed scaling, while it is an empirical
 424 parameter (a_c) for the Carazzo et al. (2014) scaling.

425 To account for uncertainties in the experimental and observational datasets,
 426 we use a Monte Carlo method. For each variable (plume height, source buoyancy
 427 flux or mass eruption rate, and environment conditions), we assume a gaussian
 428 distribution centered on the estimated mean and of standard deviation chosen
 429 to match the estimated 95% confidence interval. We create 1000 samples of each
 430 variable. For each scaling, we thus obtain 1000 values of the fitting parameters
 431 (e.g. $\frac{\beta}{\alpha}$ for our proposed scaling) and the determination coefficient of the fit
 432 (R^2), from which we estimate their mean values and the 95% confidence interval,
 433 which are taken as the 2.5th and 97.5th quantiles of their distributions. To
 434 assess whether one scaling better performs than another, we test whether the
 435 5th quantile of the distribution of pairwise difference of associated determination
 436 coefficients is larger than 0.

437 **4. Results**

438 *4.1. Plume height predictions*

439 For each scaling, Figure 5 shows the measured maximum plume height as a
 440 function of predicted height for laboratory experiments. The top panels show
 441 the three analytical scalings (Morton et al. (1956), Hewett et al. (1971) and this
 442 study) while the bottom panels show the scalings from functional approxima-
 443 tions of the plume height (Degruyter and Bonadonna (2012), Woodhouse et al.
 444 (2013) and Carazzo et al. (2014)).

445 For analytical scalings, the classical H^{MTT} , which does not account for wind
 446 effects, and the Hewett et al. (1971) scaling, derived assuming $\mathcal{W}^* \gg 1$ (panels
 447 (a) and (b) of Figure 5, respectively), poorly explain the plume height variability
 448 resulting from various environmental and source conditions with $R^2 = 0.51_{0.37}^{0.64}$
 449 and $R^2 = 0.21_{0.15}^{0.26}$, respectively (subscript/superscript indicate the 95% confi-
 450 dence interval). In contrast, the proposed analytical scaling outperforms all scal-
 451 ings, analytical and functional, for the plume height (panel (c), $R^2 = 0.88_{0.8}^{0.94}$).
 452 The best fit is found for $\frac{\beta}{\alpha} = 7.7_{5.3}^{10.9}$. For functional scalings, the Degruyter
 453 and Bonadonna (2012) and Woodhouse et al. (2013) (panels (d) and (e) of Fig-
 454 ure 5 respectively) scalings capture the plume height variations resulting from
 455 different wind forcings, although they leave about 20 – 25% of height variance
 456 unexplained ($R^2 = 0.74_{0.6}^{0.84}$ and $R^2 = 0.72_{0.56}^{0.83}$ respectively). Best fit for these
 457 scalings are found for $\frac{\beta^2}{\alpha^{\frac{3}{2}}} = 0.54_{0.37}^{0.74}$ and $\frac{\beta}{\alpha} = 3.4_{2.2}^{4.8}$ respectively. Note that here,
 458 we define $\mathcal{R}_g^{wind} = (\frac{W}{H_{tank}N})^2$ (required in the Woodhouse et al. (2013) scaling)
 459 due to the absence of a wind gradient in the Carazzo et al. (2014) experiments
 460 (where H_{tank} is the depth of the tank used). Despite our modification its origi-
 461 nal formulation, the Carazzo et al. (2014) scaling outperforms other functional
 462 scalings with $R^2 = 0.87_{0.78}^{0.93}$ ($a_c = 3.4_{2.4}^{4.7}$ panel (f)). The distribution of pairwise
 463 differences of R^2 indicates that R^2 for this scaling is not significantly different
 464 (at the 95% level) to that for our proposed analytical scaling.

465 We repeat the same analysis using data from explosive eruptions instead of
 466 laboratory experiments in Figure 6. With natural data, the differences among
 467 the performances of the scalings are less pronounced. The least successful pre-
 468 diction is obtained with the Hewett et al. (1971) scaling which assume a very
 469 strong wind, with $R^2 = 0.5_{0.36}^{0.62}$. Predictions using the Morton et al. (1956),
 470 Equation 24 and Degruyter and Bonadonna (2012) scalings are significantly
 471 better than the Hewett et al. (1971) scalings with $R^2 = 0.58$. The Woodhouse
 472 et al. (2013) and Carazzo et al. (2014) scalings outperform other scalings with
 473 $R^2 \simeq 0.63$. R^2 of these two scalings are not significantly different at a 95%
 474 confidence level, but they are significantly larger than R^2 of all other scalings.
 475 In general, the relatively weak performances with natural data give poor con-

476 straints on fit parameters, and in particular, the entrainment coefficients ratio
 477 which values are however compatible with the one constrained experimentally
 478 within the 95% uncertainty.

479 4.2. Entrainment coefficients

480 Applying the Carazzo et al. (2014) experimental data to test plume height
 481 scalings (Figure 5), we obtain $\frac{\beta^2}{\alpha^{\frac{2}{3}}} = 0.54_{0.37}^{0.74}$, $\frac{\beta}{\alpha} = 3.4_{2.2}^{4.8} \pm 2$, and $\frac{\beta}{\alpha} = 7.7_{5.3}^{10.9}$ for
 482 the Degruyter and Bonadonna (2012), Woodhouse et al. (2013) and proposed
 483 scalings respectively. However, the expression from Woodhouse et al. (2013) is
 484 valid for plumes rising in linear wind gradient. Thus, $\frac{\beta}{\alpha}$ can not be rigorously
 485 constrained using this scaling and the Carazzo et al. (2014) dataset (uniform
 486 wind). The constraint obtained from Degruyter and Bonadonna (2012) relies on
 487 the arbitrary assumption that the Morton et al. (1956) and Hewett et al. (1971)
 488 scalings can be linearly superposed to predict the buoyancy flux of a plume
 489 rising under intermediate wind forcing ($0 < \mathcal{W}_0^* < 1$). R^2 value for this scaling
 490 suggests that their assumption is not fully adequate. In contrast, our scaling is
 491 analytical, and applicable to buoyant jets rising in uniform intermediate cross-
 492 flow, which corresponds to experimental conditions of Carazzo et al. (2014).
 493 Figure S4 shows that a majority of experiments fulfill the assumptions made in
 494 deriving the proposed scaling (cf Section 2.2), which is further corroborated by
 495 the good prediction of plume height for these experiments.

496 Figure 7 combines existing constraints on entrainment coefficients from pre-
 497 vious studies with the new constraint $\frac{\beta}{\alpha} = 7.7_{5.3}^{10.9}$. The large range of $\mathcal{R}i_0 - \mathcal{W}_0^*$
 498 used in Carazzo et al. (2014) suggests that this constraint holds across the large
 499 variety of regimes in which α and β have been experimentally constrained in
 500 previous studies (Figure 7). The plausible space for the choice of a pair (α, β)
 501 is considerably reduced. This new constraint may help reduce uncertainties
 502 in scaling and integral plume model arising from uncertainties in entrainment
 503 coefficient. We further explore this result in the discussion section.

504 4.3. Best set of parameters to evaluate mass eruption rate

505 For natural eruptions, it is common to regress the logarithm of the mass
 506 eruption rate as a function of the logarithm of the plume height to obtain an
 507 empirical relationship between mass eruption rate and plume height (e.g. Mastin
 508 (2014)). Here, to get the best possible predictions for mass eruption rates,
 509 we perform a multiple linear regression where the dependent variable is the
 510 logarithm of the mass eruption rate $\log(M_0)$ and the predictors are $\log(H_{max})$,
 511 $\log(N)$ and $P_{scaling}^w$, where $P_{scaling}^w$ is related to the parameter used to account
 512 for wind forcing in the different scalings:

- 513 • $\log(W)$ for the Hewett et al. (1971) scaling
- 514 • $Ri_{gw}^{-\frac{1}{2}}$ for the Woodhouse et al. (2013) scaling
- 515 • $\mathcal{V}_0^*$ for the Degruyter and Bonadonna (2012) scaling
- 516 • $\mathcal{T}_0^*$ for the Carazzo et al. (2014) scaling
- 517 • $\mathcal{W}_0^*$ for our proposed scaling (section 2).

518 For the latter four scalings, we developed the expression of the logarithm of the
 519 scaled mass eruption rate at order 1 in the parameter used to account for wind
 520 forcing in each scaling to simplify the expression of $P_{scaling}^w$. Large differences
 521 between the original scalings and our simplified linear regression model are thus
 522 expected when $Ri_{gw}^{-\frac{1}{2}}$, $\mathcal{V}_0^*$, $\mathcal{T}_0^*$ or $\mathcal{W}_0^*$ are not small with respect to 1, but the
 523 linearization enables to obtain simple, compact empirical relationships between
 524 plume height, mass eruption rate, and environmental conditions.

525 Figure 8 shows the regressed mass eruption rate as a function of $\log(M_0)$.
 526 Associated regression coefficients are indicated in Table 2. Differences among the
 527 different predictions are small, with the mean R^2 varying between 0.72 and 0.77.
 528 The largest R^2 is found when using the set of parameters of the Degruyter and
 529 Bonadonna (2012) and Carazzo et al. (2014) scaling (no significant R^2 difference
 530 between these scalings). When only using plume height as a predictor (like
 531 Mastin (2014)), we find $R^2 = 0.70_{0.64}^{0.76}$. R^2 is always significantly larger when

532 using the Brunt Väisälä frequency or a parameter accounting for wind forcing
 533 as a dependent variable. We note that using scaling relationships accounting
 534 for environmental parameters instead of empirical relationships between plume
 535 height and mass eruption rate may prove critical in the future as global warming
 536 is expected to impact the height reached by volcanic plumes (Aubry et al., 2016).

537 5. Discussion

538 5.1. New constraint on entrainment coefficients: Implications

539 The application of the proposed analytical scaling to the Carazzo et al.
 540 (2014) experiments constrains the ratio of entrainment coefficients $\frac{\beta}{\alpha} = 7.7_{5.3}^{10.9}$.
 541 Critically, the large range of Re_0 used in Carazzo et al. (2014) suggests that the
 542 proposed constraint holds across regimes where the radial entrainment coeffi-
 543 cient α is known to vary significantly. Our result thus suggests that variations
 544 in β are approximately proportional to those in α . For models accounting for
 545 variable α (e.g. Carazzo et al. (2008)), the proposed constraint of $\frac{\beta}{\alpha} \simeq 8$ con-
 546 sequently provides an empirical framework to take into account corresponding
 547 variations of β .

548 To illustrate this application, we calculate plume trajectories for experiments
 549 23 ($W_0^* = 4.3 \cdot 10^{-2}$) and 27 ($W_0^* = 3.5 \cdot 10^{-3}$) of the Carazzo et al. (2014)
 550 dataset using the Carazzo et al. (2008) integral model. Figure 9 shows (i) the
 551 observed plume trajectories (on each panel), (ii) the modeled plume trajectories
 552 with constant β (panels (a) and (c)) and (iii) modeled plume trajectories with
 553 constant $\frac{\beta}{\alpha}$ (panels (b) and (d)). We calculate trajectories for values of β varying
 554 from 0.1 to 1 with an increment of 0.1, and for values of $\frac{\beta}{\alpha}$ varying from 5 to 11
 555 with an increment of 1. For each modeled trajectory, we calculate the relative
 556 root-mean squared error on the plume trajectory as $E = \sqrt{\frac{\int_0^{x_{max}} (z_{mod} - z_{obs})^2 dx}{\int_0^{x_{max}} z_{obs}^2 dx}}$
 557 where z_{mod} is the modeled height of the centerline, z_{obs} the observed height,
 558 and x_{max} is the horizontal distance from the source. For experiments 23 and
 559 27, when using a constant β in the integral plume model, optimal values to
 560 best match the observed plume trajectories are different for experiment 23 ($\beta =$

0.5–0.7) and 27 ($\beta = 0.2$ –0.4). In addition, for experiment 27, trajectories with the lowest error E overestimate the maximum plume height. These problems disappear when using a constant $\frac{\beta}{\alpha}$ in the integral plume model. We find a best match to plume trajectories with $\frac{\beta}{\alpha} = 6 - 8$ for both experiments. These values of the ratio $\frac{\beta}{\alpha}$ are close to the mean value of 7.7 estimated using our proposed scaling. Plume height is also well reproduced for experiment 27. Further testing using the integral model, which is not the purpose of this study, will be required but these exploratory results show that the new constraint may not only help to reduce uncertainties on the values of entrainment coefficients, but may also help improve entrainment parameterization.

Note that the recent study of Folch et al. (2016) proposes to account for local variations of β , but assumes that β decreases with the local Richardson number on the basis of laboratory experiments, while α increases with it. In contrast, the good prediction of our proposed scaling for the plume height suggests that both parameters vary similarly.

5.2. Plume shape and the Morton et al. (1956) similarity theory.

The Morton et al. (1956) model, on which most scalings and integral models of volcanic plume rely, assumes that the plume shape is self-similar. In the presence of wind, the flow is not vertically symmetric and the self-similarity hypothesis is not obviously justified and needs to be verified. To this end, for each of the Carazzo et al. (2014) experiments, we measure the average tracer concentration along plume profiles perpendicular to the centerline using the stack of all images recorded for the experiment. Here, the centerline is defined as the peak of the tracer concentration. For $\mathcal{R}i_0^{wind} = \frac{\mathcal{R}i_0}{\mathcal{W}_0^2} \simeq 10^3$, the rise is approximately symmetric with respect to the vertical and plume profiles are well approximated by a gaussian function at all heights. However, for smaller $\mathcal{R}i_0^{wind}$, plume profiles are skewed to the downwind side. To quantify this asymmetry, we separate each tracer profile into a downwind and upwind half on either side of the peak of the profile. Each half is well approximated by a gaussian fit (Figure S5) from which we obtain the characteristic downwind width (r_{down})

591 and upwind width (r_{up}). From these widths, we define the “plume asymmetry
592 factor”:

$$A_s = 2 \times \frac{r_{down} - r_{up}}{r_{down} + r_{up}}. \quad (26)$$

593 Figure 10 shows measured A_s as a function of $\mathcal{R}i_0^{wind}$. We use only profiles
594 for which R^2 of the gaussian fit of each half are larger than 0.9. In addition,
595 we use profiles measured at heights below 50% of the maximum height due to
596 partial overlapping of the rising plume and descending or spreading umbrella
597 cloud in the upper plume half for some experiments (Figure S5). For the largest
598 $\mathcal{R}i_0^{wind}$ ($\simeq 10^3$), the plume is symmetric around the vertical axis and A_s does
599 not exceed 0.23 in absolute value. As $\mathcal{R}i_0^{wind}$ decreases, maximum values of
600 A_s increases, indicating that the plume is skewed to the downwind side. For a
601 fixed $\mathcal{R}i_0^{wind}$, A_s tends to increase with height. For $\mathcal{R}i_0^{wind} < 10$, A_s reaches
602 values that exceed the range found for the largest $\mathcal{R}i_0^{wind}$ experiment indicating
603 a significant skewness. For $\mathcal{R}i_0^{wind} < 1$, A_s often reaches values above 0.6,
604 indicating that the downwind plume width is about twice the upwind width.
605 Note that $\mathcal{R}i_0^{wind}$ seems to be a better control regime parameter on A_s than W_0^* ,
606 and is also the parameter that seems to control the transition in plume style
607 (Figure 4). $\mathcal{R}i_0^{wind}$ thus seems to control both the large scale features (plume
608 style) and the internal detail (profile shape) of the plume shape.

609 Changes in shape imply that the similarity hypothesis of Morton et al. (1956)
610 is locally violated and that the rate of entrainment is different at the downwind
611 and upwind edges of the plume. In numerical simulations, Suzuki and Koyaguchi
612 (2015) also observed velocity profiles skewed to the downwind side. They deduce
613 that entrainment rate is larger to the upwind side because of the sharper upwind
614 velocity gradient. We do not measure local velocity in the Carazzo et al. (2014)
615 experiments, but a plume skewed to the downwind side requires a larger mass
616 flux downwind and thus a larger downwind entrainment. A large variety of
617 transient turbulent features, depending on the dynamical regimes, can explain
618 asymmetric plume shape and entrainment rate (Mahesh, 2013). In particular,

619 based on 3D numerical simulations, Muppidi and Mahesh (2008) show that
 620 downwind entrainment contributes to up to 90% of total entrainment for a jet
 621 in a crossflow with $\mathcal{W}_0^* \simeq 0.18$. They find that the contribution of downwind
 622 entrainment to the total entrainment increases as the plume rises, which is
 623 consistent with Figure 10. Enhanced downwind entrainment occurs because the
 624 jet acts as an obstacle for the crossflow. The pressure field is characterized by
 625 a low pressure inside the jet, and two high pressure zones at the upwind edge
 626 of the jet where the crossflow is decelerated and downstream of the jet where
 627 it is accelerated. Upwind, pressure gradients are confined very close to the jet
 628 edge and little fluid from the crossflows is thus entrained. Downwind, however,
 629 pressure gradients extend far behind the jet edge and entrainment of crossflow
 630 fluid into the jet is thus enhanced (Muppidi and Mahesh, 2008).

631 Evidence for violation of the self-similarity hypothesis leaves space for im-
 632 provement of integral models. In particular, laboratory and numerical experi-
 633 ments from which entrainment is directly measured are mostly restricted to jets,
 634 and to a few values of the regime parameter $\mathcal{W}_0^*$. How the entrainment rate,
 635 and thus α and β , vary across the $\mathcal{R}i_0$ - $\mathcal{W}_0^*$ in which explosive volcanic eruptions
 636 occur remains an open question. In addition, integral plume models use a pre-
 637 scribed shape for buoyancy and velocity profiles, generally parameterized using
 638 a distribution with a single shape parameter (the plume width). To account
 639 for changes in plume shape, distributions with two shape parameters could be
 640 used to describe the plume profiles (e.g. a width and a skewness). Changes in
 641 the second shape parameter could be described by an empirical equation, based
 642 on laboratory or numerical experiments. Further work to better characterize
 643 variations of entrainment rates and changes in plume shapes is required before
 644 including such effects in integral plume models, but would lead to an improved
 645 prediction of plume height and an additional prediction of particle and gas dis-
 646 tribution in the plume which are a critical outputs for dispersion models (Folch
 647 and Felpeto, 2005).

648 5.3. Future challenges for testing scaling and integral plume models

649 5.3.1. Laboratory experiments

650 Ideally, validations of volcanic plume models on the basis of analog labora-
 651 tory experiments should rest on a dataset spanning the same range of source
 652 Richardson numbers ($\mathcal{R}i_0$) and wind to source velocity ratios ($\mathcal{W}_0^*$) as natural
 653 explosive eruptions. However, Carazzo et al. (2014) show that most existing
 654 datasets do not fulfill this condition. To test whether datasets with restricted
 655 $\mathcal{R}i_0 - \mathcal{W}_0^*$ ranges allow a correct assessment of plume models, we use the Con-
 656 tini et al. (2011) experiments to test height predictions of the six scalings (the
 657 $\mathcal{R}i_0 - \mathcal{W}_0^*$ space covered by this study is shown in Figure 4 by blue shadings).

658 Predicted plume heights from Contini et al. (2011) are shown in Figure 11.
 659 In contrast to Figure 5, all scalings accounting for wind forcing show excellent
 660 performance in capturing plume height variability ($R^2 > 0.9$). Beyond the
 661 restricted $\mathcal{R}i_0 - \mathcal{W}_0^*$ used by Contini et al. (2011), the few values used for F_0
 662 and N (source buoyancy flux and stratification), and thus H^{MTT} (red dashed
 663 lines on panel (a), Figure 11), facilitate fitting by scalings using an additional
 664 parameter related to wind forcing. While a restricted $\mathcal{R}i_0 - \mathcal{W}_0^*$ parameter space
 665 may be justified for some applications, such as engineering oriented applications
 666 (e.g., Huq (1997); Contini et al. (2011)), the comparison of Figures 5 and 11
 667 demonstrates that it can lead to an equivocal model validation for applications
 668 to volcanic plumes.

669 As a final remark to this section, experiments with more complex wind profile
 670 would enable a quantitative comparison of scalings that are based on the aver-
 671 age wind speed (e.g. Degruyter and Bonadonna (2012)) to those developed with
 672 an average wind vertical gradient (e.g. Woodhouse et al. (2013)). In particular,
 673 that the Woodhouse et al. (2013) and Carazzo et al. (2014) scalings best predict
 674 the height of natural eruptions may highlight the important role of wind gradi-
 675 ents for natural eruption dynamics. However, these scalings reasonably capture
 676 the plume height variability from the Carazzo et al. (2014) experiments which
 677 also suggests that effects of wind gradient and constant wind may be compa-

678 rable over certain W_0^* ranges. Appropriate laboratory experiments with wind
679 gradients will resolve this issue.

680 5.3.2. Explosive eruptions

681 For explosive eruptions, our initial study used only the 25 eruptions from
682 the Mastin (2014) dataset. Significant differences - in terms of the performance
683 of each scaling as well as best fit parameters - appear when we use the newly
684 compiled dataset of 94 eruptions (not shown). These differences highlight the
685 need to keep improving datasets with plume height and source conditions es-
686 timated independently, in particular by including eruptions spanning a large
687 range of source and atmospheric conditions. Our study shows that despite large
688 uncertainties in natural eruption parameters, statistically significant differences
689 between scalings performance exist. An improved assessment of uncertainties in
690 eruption parameters will further improve the comparison of scalings, and plume
691 models in general.

692 Last, it is commonly thought that atmospheric water vapor entrained inside
693 a volcanic plume may eventually condense as the plume rises and cools. The
694 release of latent heat with condensation would increase the plume buoyancy flux
695 which, in turn, will increase the plume height (Morton, 1957; Woods, 1993).
696 Numerical modeling results suggest that for $M_0 \ll 10^6 kg.s^{-1}$, this additional
697 flux of buoyancy dominates the eruption source buoyancy flux related to ash and
698 clast heat, and depends mostly on atmospheric humidity (e.g., Woods (1993);
699 Degruyter and Bonadonna (2012); Woodhouse et al. (2013); Mastin (2014)).

700 To verify the impact of humidity on plume height inferred from models, we
701 test how residual heights from Figure 6 depend on relative humidity at vent
702 altitude (Figure 12). Positive residuals are expected for eruptions impacted by
703 condensation of entrained atmospheric water vapor, because the tested scalings
704 do not account for condensation of entrained water vapor. Figure 12 shows
705 that relative humidity at vent is indeed positively correlated with the residual
706 plume height. The correlation is significant for all scaling used to calculate
707 a residual, and is stronger when calculated with the only eruptions for which

708 $M_0 \leq 10^6 kg.s^{-1}$. Our results thus suggest that condensation of entrained water
709 vapor increase the plume height. Further analysis of humidity impact is beyond
710 the scope of this paper, but it would be valuable to test if accounting for the
711 condensation of entrained atmospheric water vapor in integral models of volcanic
712 plumes improves plume height prediction.

713 6. Conclusions

714 In this study, we derive a new analytical scaling for buoyant plumes rising
715 into a density-stratified uniform crossflow of intermediate strength ($\mathcal{W}_0^*, \mathcal{V}_0^* \ll$
716 1). This scaling, along with others commonly used in volcanology (cf section
717 1), is tested using a dataset of 27 analog experiments on buoyant jets rising in
718 density stratified uniform crossflow (Carazzo et al., 2014) and a new dataset of 94
719 explosive eruption phases. In contrast to previous studies, our experimental data
720 span similar dynamical conditions as explosive eruptions. Our work provides a
721 benchmark comparison between scalings for volcanic plume heights and supports
722 eight main conclusions:

- 723 1. Our proposed scaling best predicts heights of plumes from analog exper-
724 iments with uniform crossflow and highlights the key control of the wind
725 speed over buoyant jet source velocity ratio ($\mathcal{W}_0^*$) on the flow.
- 726 2. The application of the scaling to predict the height of laboratory exper-
727 iments suggests that the ratio of the wind entrainment parameter β to
728 the radial entrainment parameter α is constant through a large span of
729 dynamical regimes, with $\frac{\beta}{\alpha} = 7.7_{5.3}^{10.9} \pm 3$ (95% confidence interval). This
730 constraint is applied in an integral model of buoyant jet with α depending
731 on the local Richardson number and seems to improve plume trajectories
732 predictions.
- 733 3. The Woodhouse et al. (2013) and Carazzo et al. (2014) scalings, which
734 includes effects of wind gradients, best captures the heights of natural
735 explosive eruptions.

- 736 4. Empirical multilinear regression using the plume height, stratification, and
737 a wind regime parameter slightly but significantly improve mass eruption
738 rate predictions compared to regression using plume height only.
- 739 5. Experimental datasets spanning a narrow range $\mathcal{R}i_0$ - $\mathcal{W}_0^*$ parameter space
740 do not distinguish plume model performance.
- 741 6. The regime parameter $\mathcal{R}i_{wind}$ seems to control transition in plume shape
742 (strong, distorted and weak plumes), i.e., if a plume overshoots its level of
743 neutral buoyancy and if it spreads up- and downwind, or only downwind.
- 744 7. Residual plume height is positively correlated with relative humidity at
745 vent, which suggests that condensation of entrained water vapor increases
746 plume height.
- 747 8. Despite the successful prediction of our scaling for analog plume heights,
748 the plume shape is not self-similar in the presence of a crossflow and the
749 Morton et al. (1956) similarity hypothesis is thus violated in the presence
750 of wind. This conclusion is not new but is rarely discussed for volcanic
751 plumes. It leaves space for entrainment and plume shape parameterization
752 can be improved in integral model.

753 One main contribution of this work is to provide a more accurate constraint on
754 the entrainment coefficients applied in volcanic plume models generally. This
755 work will improve consistency in entrainment parameter values used by differ-
756 ent authors, which is the main cause of uncertainty in volcanic plume height
757 predictions by integral plume models (Costa et al., 2016). A second major
758 contribution is the newly compiled database of eruption parameters will also
759 contribute to improved evaluation of plume models.

760 Acknowledgments

761 This study has been greatly improved by the comments of two anonymous re-
762 viewers and Arnau Folch. The authors wish to thank Daniele Contini for kindly
763 providing experimental data on plume rise in stable crossflows. The authors
764 warmly thank Katharina Unglert, Wim Degruyter and Costanza Bonadonna,

765 who provided feedback at the early stage of this work. We also thank all authors
 766 whose studies enabled us to compile the database in Table S2, as well as the
 767 Global Volcanism Program which Bulletin Report are a critical source of infor-
 768 mation. We particularly grateful to all scientists who kindly took time to pro-
 769 vide additional details, dataset, unpublished results or advise which significantly
 770 contributed to improve the compiled database: Daniele Andronico, Marina
 771 Belousova and Alexander Belousov, Benjamin Bernard, Costanza Bonadonna,
 772 David Fee, Akihiro Hashimoto, David Kratzmann, Jessica Larsen, Jean-Luc
 773 Le Pennec, Larry Mastin, Fukashi Maeno, Michael Ort, Marco Pistolesi, Pe-
 774 ter Webley. We also acknowledge the use of NCEP Reanalysis data and 20th
 775 Century reanalysis, provided by the NOAA/OAR/ESRL PSD, Boulder, Col-
 776 orado, USA, from their Web site at <http://www.esrl.noaa.gov/psd/>. Support
 777 for the Twentieth Century Reanalysis Project version 2c dataset is provided by
 778 the U.S. Department of Energy, Office of Science Biological and Environmental
 779 Research (BER), and by the National Oceanic and Atmospheric Administra-
 780 tion Climate Program Office. Thomas J. Aubry acknowledges funding from the
 781 University of British Columbia through a Four Year Fellowship and from the
 782 Ecole Normale Supérieure de Cachan through a Eleve Fonctionnaire Stagiaire
 783 scholarship. Thomas J. Aubry and A. Mark Jellinek were supported by Natural
 784 Sciences and Engineering Research Council of Canada during completion of this
 785 work. Thomas J. Aubry and Guillaume Carazzo were partially supported by a
 786 grant from the Institut National des Sciences de l’Univers (INSU-CNRS).

787 **Appendix A - Degruyter and Bonadonna (2012) scaling for plume** 788 **height**

789 In this section, we clarify how we obtained an expression for the plume height
 790 for the Degruyter and Bonadonna (2012) scaling (Equation 7), which originally
 791 provides an expression for the mass eruption rate (Equation 6 in their paper)
 792 by summing the mass eruption rates as scaled from the Morton et al. (1956)
 793 and Hewett et al. (1971) scalings (Equations 2 and 6).

794 First, the author's original scaling can be re-arranged to make the source
 795 buoyancy flux appear:

$$F_0 = \pi \left(\frac{2^{\frac{5}{2}} \alpha^2 N^3}{2.8^4} (H^{DB})^4 + \frac{\beta^2 N^2 W}{6} (H^{DB})^3 \right). \quad (27)$$

796 To find an expression for the plume height H^{DB} as a function of source, envi-
 797 ronmental and entrainment parameters, we have to solve a 4th order polynomial
 798 equation in H^{DB} (Equation 27). To this end, we first define the new variable
 799 $h = \frac{H^{DB}}{H^{MTT}}$ where H^{MTT} is the scaling height from Morton et al. (1956), derived
 800 for a quiescent environment (no wind). Equation 27 can then be written:

$$F_0 = \pi (\pi^{-1} F_0 h^4 + \frac{2.8^3 \beta^2 F_0^{\frac{3}{4}} W}{6 \times 2^{\frac{15}{8}} \pi^{\frac{3}{4}} \alpha^{\frac{3}{2}} N^{\frac{1}{4}}} h^3). \quad (28)$$

801 Rearranging Equation 28, the polynomial equation for h is:

$$h^4 + \frac{2.8^3 \pi^{\frac{1}{4}}}{6 \times 2^{\frac{15}{8}}} \frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^* h^3 = 1. \quad (29)$$

802 We solve Equation 29 numerically for various values of the parameter $\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*$.
 803 On the basis of the compiled database of eruption parameters, $\mathcal{V}_0^*$ varies from
 804 10^{-1} to 10^1 for natural explosive eruptions, while published constraints on α
 805 and β (cf section 1) place the ratio $\frac{\beta^2}{\alpha^{\frac{3}{2}}}$ between 10^{-1} and 10^2 . Accordingly, we
 806 solve equation 29 for values of the parameter $\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*$ varying from 10^{-2} to 10^3 .
 807 Following the Woodhouse et al. (2013) approach, we use a rational function to
 808 fit h to $\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*$ and find that the function:

$$\frac{1 + 0.17 \frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^* + 0.00061 (\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*)^2}{1 + 0.48 \frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^* + 0.0072 (\frac{\beta^2}{\alpha^{\frac{3}{2}}} \mathcal{V}_0^*)^2}, \quad (30)$$

809 allows an excellent approximation of the numerical solution ($R^2 = 0.999$), jus-
 810 tifying Equation 7.

811 **Appendix B - Natural eruptions parameters uncertainties**

812 In this section, we illustrate how we estimate erupted mass, duration and
813 plume height and their uncertainties by detailing two cases for each parameter.
814 The chosen cases illustrate a well-constrained and poorly constrained case re-
815 spectively. Lastly, we explain some differences between the dataset compiled in
816 this study (Table S2) and Mastin (2014).

817 *Erupted mass*

818 The July 2013 eruption of Tungurahua illustrates a case for which there are
819 good constraints on the erupted mass. Since 2011, a network of volunteers living
820 near the volcano collects fallout samples on a daily basis during eruptive events
821 (Parra et al., 2016). This temporal frequency of sampling reduces uncertainty
822 related to, e.g., reworking of the ash deposit. This sampling was complemented
823 by a survey at the end of the eruption during which 51 additional samples
824 were collected, providing good constraints on the bulk density of the deposit.
825 In addition, Parra et al. (2016) test six different methods to extrapolate the
826 isopach and isomass maps and calculate the total erupted mass. The authors
827 found an average total mass estimate of $6.72 \times 10^8 \text{ kg}$ with estimates ranging
828 between 6.26 and $7.20 \times 10^8 \text{ kg}$ depending on the method used. We thus assumed
829 a total erupted mass of $6.7 \pm 0.5 \cdot 10^8 \text{ kg}$ for this event.

830 The June 1980 eruption of Mount St Helens, on the other hand, illustrates
831 a case for which the total erupted mass is relatively poorly constrained. The
832 only estimate (independent from plume height measurement) that we were able
833 to find is from Sarna-Wojcicki et al. (1981). First, for distal downwind sam-
834 pling sites, only the thickness of the ash deposit was measured. At these sites,
835 the mass was estimated using mass-thickness relationship based on measure-
836 ments made closer to the volcano. The authors also report that compaction of
837 the deposit may have occurred between the deposition and sampling. Last, the
838 total mass estimated ($4.5 \cdot 10^{10} \text{ kg}$) is on a discrete integration of direct mea-
839 surements of isopach area and thickness. Such integration does not account

840 for thinning of the deposit between two isopachs or beyond the last isopach
 841 mapped. The estimate provided by Sarna-Wojcicki et al. (1981) is thus a mini-
 842 mum mass estimate. We compared the mass estimated for the 18 and 25 May
 843 event by Sarna-Wojcicki et al. (1981) ($4.88 \cdot 10^{11}$ and $4.2 \cdot 10^{10}$ kg respectively)
 844 and by Bonadonna and Costa (2012) ($6 \pm 2 \cdot 10^{11}$ kg for May 18) and Pyle (1989)
 845 ($5.8 \pm 1.6 \cdot 10^{10}$ kg for May 25, extrapolated). Pyle (1989) and Bonadonna and
 846 Costa (2012), who use empirical functions (exponential or Weibull) to fit and
 847 integrate the square root of the deposit thickness vs square root of the area,
 848 find mass estimate which are $\simeq 30\%$ larger than the estimate by Sarna-Wojcicki
 849 et al. (1981) for these two events. For the June 12 event, we assume that a
 850 plausible estimate for the actual erupted mass is $\simeq 30\%$ larger than the mapped
 851 mass, and that the mapped mass is the lower bound for the confidence interval
 852 on erupted mass resulting in the value of $6.3 \pm 2.5 \cdot 10^{10}$ kg reported in Table S2.

853 For eruptions for which no uncertainty estimate for the erupted mass exists,
 854 we assumed a 50% relative uncertainty.

855 *Eruption duration*

856 The duration of the second phase of the Calbuco 2015 eruption is constrained
 857 by seismic data, observations of the growth and spread of the umbrella cloud
 858 and lightning observations to be $\simeq 6$ hours (Van Eaton et al., 2016). On the
 859 basis of up to a few minutes difference in the eruption start time estimated by
 860 visual and seismic observations, we assume a maximum uncertainty of 15 min
 861 resulting in the reported duration of 6 ± 0.25 hours in Table S2.

862 The June 15 1991 eruption of Mount Pinatubo is an example of an eruption
 863 where interpretation of the tephra deposit chronology introduces large uncer-
 864 tainties on the eruption duration. Koyaguchi (1996) suggests that the entire
 865 layer C of the June 15 deposit was accumulated during the 3 hours peak of
 866 the eruption. Although several studies seem to agree that most of layer C was
 867 likely deposited within 3 hour long, it is often suggested that the 6 hours wan-
 868 ing phase that followed the eruption peak also represents part of layer C (e.g.
 869 Paladio-Melosantos et al. (1996); Holasek and Self (1995)). Consequently, we

870 report an eruption duration of 6 ± 3 hours in Table S2. It is important to note
871 that when calculating the average plume height and associated uncertainty, we
872 account for the uncertainty on eruption duration. In the case of the June 15
873 Mount Pinatubo eruption, there is a difference $> 5\text{km}$ between the plume height
874 averaged over the first 3 hours of the eruption and averaged during the first 9
875 hours.

876 *Plume height*

877 Plume height time series of the 2010 Eyjafjallajökull eruption from a weather
878 radar and from a video camera are available in Arason et al. (2011). We com-
879 bined the weather radar and camera time series into a 6-hourly time series to
880 estimate the average plume height for each phase of this eruption. To estimate
881 the uncertainty on the average plume height, we consider the difference between
882 our estimated average, and the average calculated using only the radar or cam-
883 era time series. For example, for the first phase of this eruption, we obtain an
884 average plume height (above vent) of 4km using both datasets but only 3.4km
885 using the time series from the camera only. We attribute an average plume
886 height of $4 \pm 0.6\text{km}$ to this event. Overall, there is a good agreement between
887 plume height estimates from the camera and from the radar for the 2010 Ey-
888 jafjallajökull eruption, and the relative uncertainty on plume height does not
889 exceed 20%.

890 A good example of an eruption for which the plume height is poorly con-
891 strained is the Fuego 1971 eruption. The only report of direct plume height
892 observation we could find is from Bonis and Salazar (1973), reporting that “the
893 eruption clouds reached over $10,000\text{ m}$ in height”. The absence of any detail con-
894 cerning the method used to get this estimate, the time evolution of the plume,
895 and uncertainty related to whether the height reported is above sea level or
896 above vent level and whether “clouds” should be interpreted as the umbrella
897 cloud or the top of the plume make the number reported highly uncertain. Con-
898 sequently, we assume a mean plume height above vent of 10km , and assigned
899 a 50% uncertainty to this value, which is an upper bound for uncertainty on

900 plume height found for all eruptive phases for which we could constrain this
901 uncertainty.

902 *Differences with Mastin (2014) and concluding remarks on compiling a database*
903 *of eruptive parameters*

904 Here we report two important differences between the values in Table S2
905 and the data reported by Mastin (2014).

906 First, for the El Chichòn 1982 eruptions, the heights reported by Mastin
907 (2014) are from Table 1 of Carey and Sigurdsson (1986) and are calculated from
908 the erupted mass, the eruption duration, and an empirical equation linking
909 plume height to mass eruption rate. Thus, reported values for plume heights
910 and mass eruption rates are not independent. Although our average plume
911 height estimates are compatible, within uncertainty, with the values reported
912 by Mastin (2014), they are systematically lower by 2-2.5 km.

913 Second, for the 1992 eruptions of Mount Spurr, Mastin (2014) reports a
914 vent elevation of 3.2 km, a value close to the top of the volcano according to
915 the Global Volcanism Program. However, 1992 eruption was produced from
916 the Crater Peak vent, which has an elevation of 2.3 km (McGimsey et al.,
917 2001). Plume heights above vent level calculated from a source above sea level
918 (Gardner et al., 1998) are thus underestimated by 1km. Correcting the vent
919 elevation, using more sources for plume height and reporting the average plume
920 height instead of the absolute maximum over the eruption duration, we get
921 plume heights slightly different from Mastin (2014) although again, they are
922 compatible within uncertainty.

923 Most of the parameters reported in the compiled database (Table S2) are in
924 agreement, within uncertainty, with those reported by Mastin (2014). However,
925 the differences highlight the difficulty of producing a perfectly accurate database
926 of eruptive parameters. Even in the absence of problems such as the examples
927 given above (e.g., incorrect vent elevation), the values of eruptive parameters of
928 an eruption for which only sparse data is available will be subject to personal
929 interpretation and choice of sources, at least to some extent. Our efforts to

930 compile uncertainties on each eruptive parameter reported aims at providing
 931 a consensual range in addition to a mean value, although our estimation of
 932 uncertainty could likely be subject to discussion for some of the eruptions of
 933 Table S2. We will shortly make the database available online with a feedback
 934 system to facilitate such discussion.

935 References

- 936 Alfano F, Bonadonna C, Volentik AC, Connor CB, Watt SF, Pyle DM, Connor
 937 LJ. Tephra stratigraphy and eruptive volume of the May, 2008, Chaitén
 938 eruption, Chile. *Bulletin of Volcanology* 2011;73(5):613–30. doi:10.1007/
 939 s00445-010-0428-x.
- 940 Alfano F, Bonadonna C, Watt S, Connor C, Volentik A, Pyle DM. Reconstruc-
 941 tion of total grain size distribution of the climactic phase of a long-lasting
 942 eruption: the example of the 2008–2013 Chaitén eruption. *Bulletin of Vol-*
 943 *canology* 2016;78(7):1–21. doi:10.1007/s00445-016-1040-5.
- 944 Andronico D, Branca S, Calvari S, Burton M, Caltabiano T, Corsaro RA,
 945 Del Carlo P, Garfi G, Lodato L, Miraglia L, et al. A multi-disciplinary study
 946 of the 2002–03 Etna eruption: insights into a complex plumbing system. *Bul-*
 947 *letin of Volcanology* 2005;67(4):314–30. doi:10.1007/s00445-004-0372-8.
- 948 Andronico D, Scollo S, Caruso S, Cristaldi A. The 2002–03 Etna explosive
 949 activity: Tephra dispersal and features of the deposits. *Journal of Geophysical*
 950 *Research: Solid Earth* 2008;113(B4). doi:10.1029/2007JB005126.
- 951 Andronico D, Scollo S, Castro MDL, Cristaldi A, Lodato L, Taddeucci J. Erup-
 952 tion dynamics and tephra dispersal from the 24 November 2006 paroxysm at
 953 South-East crater, Mt Etna, Italy. *Journal of volcanology and geothermal*
 954 *research* 2014;274:78–91. doi:http://dx.doi.org/10.1016/j.jvolgeores.
 955 2014.01.009.
- 956 Andronico D, Spinetti C, Cristaldi A, Buongiorno M. Observations of Mt. Etna
 957 volcanic ash plumes in 2006: An integrated approach from ground-based and

958 polar satellite NOAAVHRR monitoring system. *Journal of Volcanology*
959 and *Geothermal Research* 2009;180(24):135–47. doi:[http://dx.doi.org/](http://dx.doi.org/10.1016/j.jvolgeores.2008.11.013)
960 10.1016/j.jvolgeores.2008.11.013; models and products of mafic explo-
961 sive activity.

962 Arason P, Petersen G, Bjornsson H. Observations of the altitude of the volcanic
963 plume during the eruption of Eyjafjallajökull, April–May 2010. *Earth System*
964 *Science Data* 2011;3(1):9–17. doi:10.5194/essd-3-9-2011.

965 Armienta M, De la Cruz-Reyna S, Morton O, Cruz O, Cenicerros
966 N. Chemical variations of tephra-fall deposit leachates for three
967 eruptions from Popocatepetl volcano. *Journal of Volcanology and*
968 *Geothermal Research* 2002;113(1):61–80. doi:[http://dx.doi.org/10.1016/](http://dx.doi.org/10.1016/S0377-0273(01)00251-7)
969 S0377-0273(01)00251-7.

970 Atlas Z, Dixon J, Sen G, Finny M, Martin-Del Pozzo A. Melt inclusions
971 from Volcán Popocatepetl and Volcán de Colima, Mexico: Melt evolution
972 due to vapor-saturated crystallization during ascent. *Journal of Volcanology*
973 and *Geothermal Research* 2006;153(3):221–40. doi:10.1016/j.jvolgeores.
974 2005.06.010.

975 Aubry TJ, Jellinek AM, Degruyter W, Bonadonna C, Radi V, Clyne M, Quainoo
976 A. Impact of global warming on the rise of volcanic plumes and implications
977 for future volcanic aerosol forcing. *Journal of Geophysical Research: Atmo-*
978 *spheres* 2016;121(22):13326–51. doi:10.1002/2016JD025405.

979 Baldridge WS, McGetchin TR, Frey FA, Jarosewich E. Magmatic evolution of
980 Hekla, Iceland. *Contributions to Mineralogy and Petrology* 1973;42(3):245–
981 58. doi:10.1007/BF00371589.

982 Belousova M, Belousov A. Frequent basaltic plinian eruptions in the history of
983 Chikurachki volcano, Kurile islands, Russia. XXVI EGS General Assembly;
984 2001. URL: [http://www.kscnet.ru/ivs/lavdi/staff/belousov/chikabs.](http://www.kscnet.ru/ivs/lavdi/staff/belousov/chikabs.pdf)
985 pdf.

986 Bernard B, Battaglia J, Proaño A, Hidalgo S, Vásconez F, Hernandez S, Ruiz M.
987 Relationship between volcanic ash fallouts and seismic tremor: quantitative
988 assessment of the 2015 eruptive period at Cotopaxi volcano, Ecuador. *Bulletin*
989 *of Volcanology* 2016a;78(11):80. doi:10.1007/s00445-016-1077-5.

990 Bernard J, Eychenne J, Le Pennec JL, Narváez D. Mass budget partitioning
991 during explosive eruptions: Insights from the 2006 paroxysm of Tungurahua
992 volcano, ecuador. *Geochemistry, Geophysics, Geosystems* 2016b;17(8):3224-
993 40.

994 Biass S, Bonadonna C. A quantitative uncertainty assessment of eruptive pa-
995 rameters derived from tephra deposits: the example of two large eruptions
996 of Cotopaxi volcano, Ecuador. *Bulletin of Volcanology* 2011;73(1):73-90.
997 doi:10.1007/s00445-010-0404-5.

998 Bitar L, Duck T, Kristiansen N, Stohl A, Beauchamp S. Lidar observations
999 of Kasatochi volcano aerosols in the troposphere and stratosphere. *Jour-*
1000 *nal of Geophysical Research: Atmospheres* 2010;115(D2). doi:10.1029/
1001 2009JD013650.

1002 Bonadonna C, Biass S, Costa A. Physical characterization of explosive volcanic
1003 eruptions based on tephra deposits: Propagation of uncertainties and sensitiv-
1004 ity analysis. *Journal of Volcanology and Geothermal Research* 2015a;296:80
1005 - 100. doi:http://dx.doi.org/10.1016/j.jvolgeores.2015.03.009.

1006 Bonadonna C, Cioni R, Pistolesi M, Elissondo M, Baumann V. Sedimentation
1007 of long-lasting wind-affected volcanic plumes: the example of the 2011 rhy-
1008 olitic Cordon Caulle eruption, Chile. *Bulletin of Volcanology* 2015b;77(2):13.
1009 doi:10.1007/s00445-015-0900-8.

1010 Bonadonna C, Costa A. Estimating the volume of tephra deposits: a new simple
1011 strategy. *Geology* 2012;:G32769-1doi:10.1130/G32769.1.

1012 Bonadonna C, Genco R, Gouhier M, Pistolesi M, Cioni R, Alfano F, Hoskuldsson
1013 A, Ripepe M. Tephra sedimentation during the 2010 Eyjafjallajökull eruption

1014 (Iceland) from deposit, radar, and satellite observations. *Journal of Geophys-*
1015 *ical Research: Solid Earth* 2011;116(B12). doi:10.1029/2011JB008462.

1016 Bonadonna C, Houghton B. Total grain-size distribution and volume of tephra-
1017 fall deposits. *Bulletin of Volcanology* 2005;67(5):441–56. doi:10.1007/
1018 s00445-004-0386-2.

1019 Bonadonna C, Pistolesi M, Cioni R, Degruyter W, Elissondo M, Baumann
1020 V. Dynamics of wind-affected volcanic plumes: The example of the 2011
1021 Cordón Caulle eruption, Chile. *Journal of Geophysical Research: Solid Earth*
1022 2015c;120(4):2242–61. doi:10.1002/2014JB011478.

1023 Bonis S, Salazar O. The 1971 and 1973 eruptions of volcán Fuego, Guatemala,
1024 and some socio-economic considerations for the volcanologist. *Bulletin of*
1025 *Volcanology* 1973;37(3):394–400. doi:10.1007/BF02597636.

1026 Bourdier JL, Pratomo I, Thouret JC, Boudon G, Vincent PM. Observations,
1027 stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano,
1028 Indonesia. *Journal of volcanology and geothermal research* 1997;79(3):181–
1029 203. doi:http://dx.doi.org/10.1016/S0377-0273(97)00031-0.

1030 Brantley SR. The eruption of Redoubt volcano, Alaska, December 14, 1989-
1031 August 31, 1990 1990;.

1032 Briggs G. Chimney plumes in neutral and stable surroundings. *Atmospheric*
1033 *Environment* 1972;6(7):507–10. doi:10.1016/0004-6981(72)90120-5.

1034 Browning T, Stone K, Bouman H, Mather T.A, Pyle D, Moore C, Martinez-
1035 Vicente V. Volcanic ash supply to the surface ocean remote sensing of bi-
1036 ological responses and their wider biogeochemical significance. *Frontiers in*
1037 *Marine Science* 2015;2(14). doi:doi:10.3389/fmars.2015.00014.

1038 Bursik M. Effect of wind on the rise height of volcanic plumes. *Geophysical*
1039 *Research Letters* 2001;28:3821–4. doi:10.1029/2001GL013393.

1040 Carazzo G, Girault F, Aubry TJ, Bouquerel H, Kaminski E. Laboratory
1041 experiments of forced plumes in a density-stratified crossflow and implica-
1042 tions for volcanic plumes. *Geophysical Research Letters* 2014;41(24):8759–66.
1043 doi:10.1002/2014GL061887.

1044 Carazzo G, Kaminski E, Tait S. On the dynamics of volcanic columns: A
1045 comparison of field data with a new model of negatively buoyant jets. *Journal*
1046 *of Volcanology and Geothermal Research* 2008;178(1):94 – 103. doi:doi:10.
1047 1016/j.jvolgeores.2008.01.002.

1048 Carey S, Sigurdsson H. The 1982 eruptions of El Chichòn volcano, Mexico (2):
1049 Observations and numerical modelling of tephra-fall distribution. *Bulletin of*
1050 *Volcanology* 1986;48(2):127–41. doi:10.1007/BF01046547.

1051 Carey S, Sparks R. Quantitative models of the fallout and dispersal of tephra
1052 from volcanic eruption columns. *Bulletin of Volcanology* 1986;48:109–25.
1053 doi:10.1007/BF01046546.

1054 Carn S, Lopez T. Opportunistic validation of sulfur dioxide in the Sarychev
1055 Peak volcanic eruption cloud. *Atmospheric Measurement Techniques*
1056 2011;4(9):1705–12. doi:10.5194/amt-4-1705-2011.

1057 Carn SA, Pallister JS, Lara L, Ewert JW, Watt S, Prata AJ, Thomas RJ,
1058 Villarosa G. The unexpected awakening of Chaitén volcano, Chile. *Eos,*
1059 *Transactions American Geophysical Union* 2009;90(24):205–6. doi:10.1029/
1060 2009E0240001.

1061 Carter AJ, Girina O, Ramsey MS, Demyanchuk YV. ASTER and field obser-
1062 vations of the 24 December 2006 eruption of Bezymianny volcano, Russia.
1063 *Remote Sensing of Environment* 2008;112(5):2569–77. doi:10.1016/j.rse.
1064 2007.12.001.

1065 Cassidy M, Helo C, Castro J, Muir D, Troll V. The magmatic conditions, from
1066 storage to surface preceding effusive and explosive eruptions at Kelud volcano.

1067 In: AGU Fall Meeting Abstracts. 2015. URL: [http://adsabs.harvard.edu/](http://adsabs.harvard.edu/abs/2015AGUFM.V13B3107C)
1068 [abs/2015AGUFM.V13B3107C](http://adsabs.harvard.edu/abs/2015AGUFM.V13B3107C).

1069 Castro J, Lowenstern J, Pallister J, Eichelberger J. Simultaneous explosive and
1070 effusive activity at Chaitén volcano, Chile. In: AGU Fall Meeting Abstracts.
1071 2010. URL: [2010AGUFM.V34B..08C](http://adsabs.harvard.edu/abs/2010AGUFM.V34B..08C).

1072 Castruccio A, Clavero J, Segura A, Samaniego P, Roche O, Le Pennec JL,
1073 Droguett B. Eruptive parameters and dynamics of the april 2015 sub-
1074 plinian eruptions of calbuco volcano (southern chile). Bulletin of Volcanology
1075 2016;78(9):62. doi:10.1007/s00445-016-1058-8.

1076 Caudron C, Taisne B, Garcés M, Alexis LP, Mialle P. On the use of remote in-
1077 frasound and seismic stations to constrain the eruptive sequence and intensity
1078 for the 2014 Kelud eruption. Geophysical Research Letters 2015;42(16):6614–
1079 21. doi:10.1002/2015GL064885.

1080 Chen CJ, Rodi W. Vertical turbulent buoyant jets: a review of experimental
1081 data. NASA STI/Recon Technical Report A 1980;80:23073.

1082 Christiansen RL, Peterson DW. Chronology of the 1980 eruptive activity. US
1083 Geol Surv Prof Pap 1981;1250:17–30.

1084 Collins S, Pyle D, MacLennan J. Melt inclusions track pre-eruption storage and
1085 dehydration of magmas at etna. Geology 2009;37(6):571–4. doi:10.1130/
1086 G30040A.1.

1087 Compo G, Whitaker J, Sardeshmukh P, Matsui N, Allan R, Yin X, Gleason E,
1088 Vose R, Rutledge G, Bessemoulin P, et al. The twentieth century reanalysis
1089 project. Quarterly Journal of the Royal Meteorological Society 2011;137:1–28.

1090 Contini D, Donateo A, Cesari D, Robins A. Comparison of plume rise mod-
1091 els against water tank experimental data for neutral and stable crossflows.
1092 Journal of Wind Engineering and Industrial Aerodynamics 2011;99(5):539–
1093 53. doi:10.1016/j.jweia.2011.02.003.

1094 Coombs M, Sisson T, Bleick H, Henton S, Nye C, Payne A, Cameron C, Larsen
1095 J, et al. Andesites of the 2009 eruption of Redoubt Volcano, Alaska. *Journal*
1096 *of Volcanology and Geothermal Research* 2013;259:349–72. doi:10.1016/j.
1097 *jvolgeores*.2012.01.002.

1098 Corradini S, Merucci L, Prata A, Piscini A. Volcanic ash and SO₂ in the 2008
1099 Kasatochi eruption: Retrievals comparison from different IR satellite sensors.
1100 *Journal of Geophysical Research: Atmospheres* 2010;115(D2). doi:10.1029/
1101 2009JD013634.

1102 Costa A, Suzuki Y, Cerminara M, Devenish B, Ongaro TE, Herzog M, Eaton
1103 AV, Denby L, Bursik M, de' Michieli Vitturi M, Engwell S, Neri A, Barsotti
1104 S, Folch A, Macedonio G, Girault F, Carazzo G, Tait S, Kaminski E, Mastin
1105 L, Woodhouse M, Phillips J, Hogg A, Degruyter W, Bonadonna C. Results
1106 of the eruptive column model inter-comparison study. *Journal of Volcanology*
1107 *and Geothermal Research* 2016;doi:10.1016/j.*jvolgeores*.2016.01.017.

1108 Costa F, Andreastuti S, de Maisonneuve CB, Pallister JS. Petrological in-
1109 sights into the storage conditions, and magmatic processes that yielded the
1110 centennial 2010 Merapi explosive eruption. *Journal of Volcanology and*
1111 *Geothermal Research* 2013;261:209–35. doi:http://dx.doi.org/10.1016/
1112 *j.jvolgeores*.2012.12.025.

1113 Cronin S, Hedley M, Neall V, Smith R. Agronomic impact of tephra fallout from
1114 the 1995 and 1996 Ruapehu Volcano eruptions, New Zealand. *Environmental*
1115 *Geology* 1998;34(1):21–30. doi:10.1007/s002540050253.

1116 Degruyter W, Bonadonna C. Improving on mass flow rate estimates of vol-
1117 canic eruptions. *Geophysical Research Letters* 2012;39(16). doi:10.1029/
1118 2012GL052566.

1119 Dellino P, Dioguardi F, Mele D, DAddabbo M, Zimanowski B, Bttner R,
1120 Doronzo D, Sonder I, Sulpizio R, Drig T, La Volpe L. Volcanic jets, plumes,

1121 and collapsing fountains: evidence from large-scale experiments, with partic-
 1122 ular emphasis on the entrainment rate. *Bulletin of Volcanology* 2014;76(6).
 1123 doi:10.1007/s00445-014-0834-6.

1124 Devenish B. Estimating the total mass emitted by the eruption of Eyjafjal-
 1125 lajökull in 2010 using plume-rise models. *Journal of Volcanology and Geother-*
 1126 *mal Research* 2016;doi:10.1016/j.jvolgeores.2016.01.005.

1127 Eichelberger J, Keith T, Miller T, Nye C. The 1992 eruptions of Crater Peak
 1128 vent, Mount Spurr volcano, Alaska: chronology and summary. *US Geol Surv*
 1129 *Bull* 1995;2139:1–18.

1130 Ekstrand Aand Webley P, Garay M, Dehn J, Prakash A, Nelson D, Dean
 1131 K, Steensen T. A multi-sensor plume height analysis of the 2009 Redoubt
 1132 eruption. *Journal of Volcanology and Geothermal Research* 2013;259:170–84.
 1133 doi:http://dx.doi.org/10.1016/j.jvolgeores.2012.09.008.

1134 Elissondo M, Baumann V, Bonadonna C, Pistolesi M, Cioni R, Bertagnini
 1135 A, Biasse S, Herrero JC, Gonzalez R. Chronology and impact of the 2011
 1136 Cordon Caulle eruption, Chile. *Natural Hazards and Earth System Sciences*
 1137 2016;16(3):675–704. doi:10.5194/nhess-16-675-2016.

1138 Eychenne J, Le Pennec JL, Ramón P, Yepes H. Dynamics of explosive parox-
 1139 ysms at open-vent andesitic systems: High-resolution mass distribution anal-
 1140 yses of the 2006 Tungurahua fall deposit (Ecuador). *Earth and Planetary*
 1141 *Science Letters* 2013;361:343–55. doi:http://dx.doi.org/10.1016/j.epsl.
 1142 2012.11.002.

1143 Fischer H, List E, Koh R, Imberger J, Brooks N. Mixing in Inland and Coastal
 1144 Waters. , 1979. doi:10.1016/B978-0-08-051177-1.50013-1.

1145 Flentje H, Claude H, Elste T, Gilge S, Köhler U, Plass-Dülmer C, Stein-
 1146 brecht W, Thomas W, Werner A, Fricke W. The Eyjafjallajökull eruption
 1147 in April 2010–detection of volcanic plume using in-situ measurements, ozone

sondes and lidar-ceilometer profiles. *Atmospheric Chemistry and Physics*
2010;10(20):10085–92. doi:10.5194/acp-10-10085-2010.

Folch A, Costa A, Macedonio G. FPLUME-1.0: An integral volcanic plume
model accounting for ash aggregation. *Geoscientific Model Development*
2016;9(1):431–50. doi:10.5194/gmd-9-431-2016.

Folch A, Felpeto A. A coupled model for dispersal of tephra during sus-
tained explosive eruptions. *Journal of Volcanology and Geothermal Research*
2005;145(34):337–49. doi:10.1016/j.jvolgeores.2005.01.010.

Folch A, Jorba O, Viramonte J. Volcanic ash forecast-application to the May
2008 Chaitén eruption. *Nat Hazards Earth Syst Sci* 2008;8(4):927–40. doi:10.
5194/nhess-8-927-2008.

Gardner CA, Cashman KV, Neal CA. Tephra-fall deposits from the 1992
eruption of Crater Peak, Alaska: implications of clast textures for erup-
tive processes. *Bulletin of Volcanology* 1998;59(8):537–55. doi:10.1007/
s004450050208.

Gaunt H, Bernard B, Hidalgo S, Proano A, Wright H, Mothes P, Criollo E,
Kueppers U. Eruptive dynamics inferred from textural analysis of ash time
series: The 2015 reawakening of Cotopaxi volcano; 2016. doi:10.1016/j.
jvolgeores.2016.10.013.

George WK, Alpert RL, Tamanini F. Turbulence measurements in an axisym-
metric buoyant plume. *International Journal of Heat and Mass Transfer*
1977;20(11):1145–54. doi:10.1016/0017-9310(77)90123-5.

Geshi N, Oikawa T. Phreatomagmatic eruptions associated with the caldera
collapse during the Miyakejima 2000 eruption, Japan. *Journal of Volcanology*
and *Geothermal Research* 2008;176(4):457–68. doi:http://dx.doi.org/10.
1016/j.jvolgeores.2008.04.013.

1174 Gilbert DJ. Pre-eruptive conditions at Lonquimay and Puyehue-Cordon Caulle
1175 volcanoes, Chile: Framework for tectonic influences. Ph.D. thesis; Christian-
1176 Albrechts Universität Kiel; 2012.

1177 Girault F, Carazzo G, Tait S, Kaminski E. Combined effects of total grain-size
1178 distribution and crosswind on the rise of eruptive volcanic columns. *Journal*
1179 *of Volcanology and Geothermal Research* 2016;doi:10.1016/j.jvolgeores.
1180 2015.11.007.

1181 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1971. In:
1182 Center for Short-Lived Phenomena, Smithsonian Institution.

1183 Global Volcanism Program . Report on Fuego (Guatemala); 1974. In: Center
1184 for Short-Lived Phenomena, Smithsonian Institution.

1185 Global Volcanism Program . Report on St. Helens (United States); 1980. In:
1186 Squires, D (ed.), *Scientific Event Alert Network Bulletin*, 5:5. Smithsonian
1187 Institution.

1188 Global Volcanism Program . Report on el chichon (mexico); 1982a. In: Mc-
1189 Clelland, L (ed.), *Scientific Event Alert Network Bulletin*, 7:3. Smithsonian
1190 Institution.

1191 Global Volcanism Program . Report on El Chichon (Mexico); 1982b. In: Mc-
1192 Clelland, L (ed.), *Scientific Event Alert Network Bulletin*, 7:4. Smithsonian
1193 Institution.

1194 Global Volcanism Program . Report on Nevado del Ruiz (Columbia); 1985a.
1195 doi:<http://dx.doi.org/10.5479/si.GVP.SEAN198511-351020>; in: McClelland,
1196 L (ed.), *Scientific Event Alert Network Bulletin*, 10:11. Smithsonian
1197 Institution.

1198 Global Volcanism Program . Report on Ruapehu (New Zealand); 1985b.
1199 doi:<http://dx.doi.org/10.5479/si.GVP.BGVN199510-241100>; in: Wunderman,
1200 R (ed.), *Bulletin of the Global Volcanism Network*, 20:10. Smithsonian
1201 Institution.

1202 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1986a. In:
1203 Center for Short-Lived Phenomena, Smithsonian Institution.

1204 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1986b. In:
1205 Center for Short-Lived Phenomena, Smithsonian Institution.

1206 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1986c. In:
1207 Center for Short-Lived Phenomena, Smithsonian Institution.

1208 Global Volcanism Program . Report on Chikurachki (Russia); 1986d. In: Mc-
1209 Clelland, L (ed.), Scientific Event Alert Network Bulletin, 11:11. Smithsonian
1210 Institution.

1211 Global Volcanism Program . Report on Kelut (Indonesia); 1990. In: McClelland,
1212 L (ed.), Bulletin of the Global Volcanism Network, 15:1. Smithsonian
1213 Institution.

1214 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1992. In:
1215 McClelland, L (ed.), Bulletin of the Global Volcanism Network, 17:4. Smithsonian
1216 Institution.

1217 Global Volcanism Program . Report on Cerro Negro (Nicaragua); 1995. In:
1218 Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 20:11. Smithsonian
1219 Institution.

1220 Global Volcanism Program . Report on Popocatepetl (Mexico); 1996a.
1221 doi:<http://dx.doi.org/10.5479/si.GVP.BGVN199604-341090>; in: Wunderman,
1222 R (ed.), Bulletin of the Global Volcanism Network, 21:4. Smithsonian
1223 Institution.

1224 Global Volcanism Program . Report on Popocatepetl (Mexico); 1996b.
1225 doi:<http://dx.doi.org/10.5479/si.GVP.BGVN199610-341090>; in: Wunderman,
1226 R (ed.), Bulletin of the Global Volcanism Network, 21:10. Smithsonian
1227 Institution.

1228 Global Volcanism Program . Report on Popocatepetl (Mexico); 1997. doi:<http://dx.doi.org/10.5479/si.GVP.BGVN199610-341090>; in: Wunderman, R
1229 (ed.), Bulletin of the Global Volcanism Network, 22:7. Smithsonian Insti-
1230 tution.
1231

1232 Global Volcanism Program . Report on Reventador (Ecuador); 2002. doi:<http://dx.doi.org/10.5479/si.GVP.BGVN200211-352010>; in: Wunderman, R
1233 (ed.), Bulletin of the Global Volcanism Network, 27:11. Smithsonian Insti-
1234 tution.
1235

1236 Global Volcanism Program . Report on Anatahan (United States); 2003a. In:
1237 Venzke, E (ed.), Bulletin of the Global Volcanism Network, 28:5. Smithsonian
1238 Institution.

1239 Global Volcanism Program . Report on Anatahan (United States); 2003b. In:
1240 Venzke, E (ed.), Bulletin of the Global Volcanism Network, 28:5. Smithsonian
1241 Institution.

1242 Global Volcanism Program . Report on Bezymianny (Russia); 2009. In: Wun-
1243 derman, R (ed.), Bulletin of the Global Volcanism Network, 34:11. Smithso-
1244 nian Institution.

1245 Global Volcanism Program . Report on Merapi (Indonesia); 2011. In: Wunder-
1246 man, R (ed.), Bulletin of the Global Volcanism Network, 36:1. Smithsonian
1247 Institution.

1248 Global Volcanism Program . Report on Cotopaxi (Ecuador); 2016. In: Ven-
1249 zke, E (ed.), Bulletin of the Global Volcanism Network, 41:4. Smithsonian
1250 Institution.

1251 Global Volcanism Report . Report on Shishaldin (United States); 1999.
1252 doi:<http://dx.doi.org/10.5479/si.GVP.BGVN199904-311360>.; in: Wun-
1253 derman, R (ed.), Bulletin of the Global Volcanism Network, 24:4. Smithsonian
1254 Institution.

1255 Gronvold K, Larsen G, Einarsson P, Thorarinsson S, Saemundsson K. The Hekla
1256 eruption 1980–1981. *Bulletin volcanologique* 1983;46(4):349–63. doi:10.1007/
1257 BF02597770.

1258 Gudmundsson A, Oskarsson N, Gronvold K, Saemundsson K, Sigurdsson O,
1259 Stefansson R, Gislason SR, Einarsson P, Brandsdottir B, Larsen G, et al.
1260 The 1991 eruption of Hekla, Iceland. *Bulletin of Volcanology* 1992;54(3):238–
1261 46. doi:10.1007/BF00278391.

1262 Gudmundsson MT, Thordarson T, Höskuldsson Á, Larsen G, Björnsson H,
1263 Prata FJ, Oddsson B, Magnússon E, Högnadóttir T, Petersen GN, et al.
1264 Ash generation and distribution from the April-May 2010 eruption of Eyjaf-
1265 jallajökull, iceland. *Scientific reports* 2012;2. doi:10.1038/srep00572.

1266 Gurenko A, Belousov A, Trumbull R, Sobolev A. Explosive basaltic vol-
1267 canism of the Chikurachki volcano (Kurile arc, Russia): Insights on pre-
1268 eruptive magmatic conditions and volatile budget revealed from phenocryst-
1269 hosted melt inclusions and groundmass glasses. *Journal of Volcanology*
1270 and Geothermal Research 2005;147(3):203–32. doi:http://dx.doi.org/10.
1271 1016/j.jvolgeores.2005.04.002.

1272 Hall M, Steele A, Mothes P, Ruiz M. Pyroclastic density currents (pdc) of the
1273 16–17 August 2006 eruptions of Tungurahua volcano, Ecuador: Geophysical
1274 registry and characteristics. *Journal of Volcanology and Geothermal Research*
1275 2013;265:78–93.

1276 Hall Mand Ramón P, Mothes P, LePennec J, García A, Samaniego P,
1277 Yepes H. Volcanic eruptions with little warning: the case of Volcán
1278 Reventador’s Surprise November 3, 2002 Eruption, Ecuador. *Revista*
1279 *geológica de Chile* 2004;31(2):349–58. doi:http://dx.doi.org/10.4067/
1280 S071602082004000200010.

1281 Harris DM, Rose W, Roe R, Thompson M, Lipman P, Mullineaux D. Radar
1282 observations of ash eruptions. *US Geological Survey professional paper*
1283 1981;1250:323–33.

1284 Hashimoto A, Shimbori Tand Fukui K. Tephra fall simulation for the erup-
1285 tions at Mt. Shinmoe-dake during 26-27 January 2011 with JMANHM. Sola
1286 2012;8:37–40. doi:10.2151/sola.2012-010.

1287 Hayer C, Carboni E, Ventress L, Povey A, Grainger R. Satellite observations
1288 of the volcanic plume from the 23rd April 2015 eruption of Calbuco volcano.
1289 volume 18 of *EGU General Assembly Conference Abstracts*; 2016. p. 17035.
1290 URL: <http://adsabs.harvard.edu/abs/2016EGUGA..1817035H>.

1291 Hewett T, Fay J, Hoult D. Laboratory experiments of smokestack plumes in a
1292 stable atmosphere. *Atmospheric Environment* 1971;5:767–89.

1293 Hildreth W, Drake R. Volcán Quizapu, Chilean Andes. *Bulletin of Volcanology*
1294 1992;54(2):93–125. doi:10.1007/BF00278002.

1295 Hill BE, Connor CB, Jarzemba MS, La Femina PC, Navarro M, Strauch W.
1296 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for
1297 future eruptions. *Geological Society of America Bulletin* 1998;110(10):1231–
1298 41. doi:10.1130/0016-7606(1998)110<1231:E0CNVN>2.3.CO;2.

1299 Hoblitt R, Wolfe E, Scott W, Couchman M, Pallister J, Javier D. The preclimac-
1300 tic eruptions of Mount Pinatubo, June 1991. *Fire and Mud: eruptions and*
1301 *lahars of Mount Pinatubo, Philippines: Philippine Institute of Volcanology*
1302 *and Seismology and University of Washington* 1996;457–511.

1303 Holasek R, Self S. GOES weather satellite observations and measurements of the
1304 May 18, 1980, Mount St. Helens eruption. *Journal of Geophysical Research:*
1305 *Solid Earth* 1995;100(B5):8469–87. doi:10.1029/94JB03137.

1306 Holasek R, Self S, Woods A. Satellite observations and interpretation of the
1307 1991 Mount Pinatubo eruption plumes. *Journal of Geophysical Research:*
1308 *Solid Earth* 1996;101(B12):27635–55. doi:10.1029/96JB01179.

1309 Hoult D, Fay J, Forney L. A theory of plume rise compared with field ob-
1310 servations. *Journal of the Air Pollution Control Association* 1969;19:585–90.
1311 doi:10.1080/00022470.1969.10466526.

1312 Hoult D, Weil J. Turbulent plume in a laminar cross flow. *Atmospheric Envi-*
1313 *ronment* 1972;6:513–31. doi:10.1016/0004-6981(72)90069-8.

1314 Hreinsdóttir S, Sigmundsson F, Roberts MJ, Björnsson H, Grapenthin R, Ara-
1315 son P, Árnadóttir T, Hólmjárn J, Geirsson H, Bennett RA, et al. Volcanic
1316 plume height correlated with magma-pressure change at Grimsvotn volcano,
1317 Iceland. *Nature geoscience* 2014;7(3):214–8. doi:10.1038/ngeo2044.

1318 Huq P. Observations of jets in density stratified crossflows. *Atmospheric Envi-*
1319 *ronment* 1997;31:2011–22. doi:10.1016/S1352-2310(97)00281-1.

1320 Hurst A, Turner R. Performance of the program ASHFALL for forecast-
1321 ing ashfall during the 1995 and 1996 eruptions of Ruapehu volcano. *New*
1322 *Zealand Journal of Geology and Geophysics* 1999;42(4):615–22. doi:10.1080/
1323 00288306.1999.9514865.

1324 Izbekov P, Sisson T, Wooden J, Bacon C. 2008 Kasatochi Eruption: SHRIMP
1325 constraints on concentration of volatiles in melt inclusions. In: *AGU Fall*
1326 *Meeting Abstracts*. volume 1; 2009. p. 1775. URL: [http://adsabs.harvard.](http://adsabs.harvard.edu/abs/2009AGUFM.V51E1775I)
1327 [edu/abs/2009AGUFM.V51E1775I](http://adsabs.harvard.edu/abs/2009AGUFM.V51E1775I).

1328 Jude-Eton T, Thordarson T, Gudmundsson M, Oddsson B. Dynamics, stratig-
1329 raphy and proximal dispersal of supraglacial tephra during the ice-confined
1330 2004 eruption at Grímsvötn volcano, Iceland. *Bulletin of volcanology*
1331 2012;74(5):1057–82. doi:10.1007/s00445-012-0583-3.

1332 Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M,
1333 Saha S, White G, Woolen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W,
1334 et al. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American*
1335 *Meteorological Society* 1996;77(3):437–71. doi:10.1175/1520-0477(1996)
1336 077.

1337 Kaminski E, Tait S, Carazzo G. Turbulent entrainment in jets with arbi-
1338 trary buoyancy. *Journal of Fluid Mechanics* 2005;526:361–76. doi:10.1017/
1339 S0022112004003209.

- 1340 Kilgour G, Blundy J, Cashman K, Mader H. Small volume andesite magmas
1341 and melt–mush interactions at Ruapehu, New Zealand: evidence from melt
1342 inclusions. *Contributions to Mineralogy and Petrology* 2013;166(2):371–92.
1343 doi:10.1007/s00410-013-0880-7.
- 1344 Koyaguchi T. Volume estimation of tephra-fall deposits from the june 15, 1991,
1345 eruption of Mount Pinatubo by theoretical and geological methods. *Fire and*
1346 *Mud: Eruptions and Lahars of Mount Pinatubo*, Philippines University of
1347 Washington Press, Seattle 1996;:583–600.
- 1348 Koyaguchi T, Ohno M. Reconstruction of eruption column dynamics on the
1349 basis of grain size of tephra fall deposits: 2. Application to the Pinatubo 1991
1350 eruption. *Journal of Geophysical Research: Solid Earth* 2001;106(B4):6513–
1351 33. doi:10.1029/2000JB900427.
- 1352 Koyaguchi T, Suzuki YJ, Kozono T. Effects of the crater on eruption column
1353 dynamics. *Journal of Geophysical Research: Solid Earth* 2010;115(7):1–26.
1354 doi:10.1029/2009JB007146.
- 1355 Kozono T, Ueda H, Ozawa T, Koyaguchi T, Fujita E, Tomiya A, Suzuki Y.
1356 Magma discharge variations during the 2011 eruptions of Shinmoe-dake vol-
1357 cano, Japan, revealed by geodetic and satellite observations. *Bulletin of vol-*
1358 *canology* 2013;75(3):695. doi:10.1007/s00445-013-0695-4.
- 1359 Kratzmann DJ, Carey S, Scasso R, Naranjo JA. Compositional variations and
1360 magma mixing in the 1991 eruptions of Hudson volcano, Chile. *Bulletin of*
1361 *Volcanology* 2009;71(4):419. doi:10.1007/s00445-008-0234-x.
- 1362 Kratzmann DJ, Carey SN, Fero J, Scasso RA, Naranjo JA. Simulations of tephra
1363 dispersal from the 1991 explosive eruptions of Hudson volcano, Chile. *Journal*
1364 *of Volcanology and Geothermal Research* 2010;190(3):337–52. doi:http://
1365 dx.doi.org/10.1016/j.jvolgeores.2009.11.021.
- 1366 Kristiansen NI, Prata AJ, Stohl A, Carn SA. Stratospheric volcanic ash emis-

1367 sions from the 13 February 2014 Kelut eruption. *Geophysical Research Letters*
 1368 2015;42(2):588–96. doi:10.1002/2014GL062307.

1369 Krotkov N, Torres O, Seftor C, Krueger A, Kostinski A, Rose W, Bluth G,
 1370 Schneider D, Schaefer S. Comparison of TOMS and AVHRR volcanic ash
 1371 retrievals from the August 1992 eruption of Mt. Spurr. *Geophysical research*
 1372 *letters* 1999;26(4):455–8. doi:10.1029/1998GL900278.

1373 Krueger A, Krotkov N, Carn S. El Chichon: The genesis of volcanic sul-
 1374 fur dioxide monitoring from space. *Journal of Volcanology and Geother-*
 1375 *mal Research* 2008;175(4):408–14. doi:http://dx.doi.org/10.1016/j.
 1376 jvolgeores.2008.02.026.

1377 Krueger A, Walter L, Schnetzler C, Doiron S. TOMS measurement of the
 1378 sulfur dioxide emitted during the 1985 Nevado del Ruiz eruptions. *Journal*
 1379 *of Volcanology and Geothermal Research* 1990;41(1-4):7–15. doi:http://dx.
 1380 doi.org/10.1016/0377-0273(90)90081-P.

1381 Kylling A. Ash and ice clouds during the Mt Kelud February 2014 eruption as
 1382 interpreted from IASI and AVHRR/3 observations. *Atmospheric Measure-*
 1383 *ment Techniques* 2016;9(5):2103–17. doi:10.5194/amt-9-2103-2016.

1384 Langmann B, Zaksek K, Hort M, Duggen S. Volcanic ash as fertiliser for the
 1385 surface ocean. *Atmospheric Chemistry and Physics* 2010;10:38913899. doi:10.
 1386 5194/acp-10-3891-2010.

1387 Lara LE. The 2008 eruption of the chaitén volcano, chile: a preliminary re-
 1388 port. *Andean geology* 2010;36(1):125–30. doi:http://dx.doi.org/10.5027/
 1389 andgeoV36n1-a09.

1390 Larsen J, Neal C, Webley P, Freymueller J, Haney M, McNutt S, Schneider D,
 1391 et al. Eruption of Alaska volcano breaks historic pattern. *Eos, Transactions,*
 1392 *American Geophysical Union* 2009;90(20):173–4.

1393 Larsen J, Schaefer J, Neal C, Kaufman A, Lu Z. The 2008 phreatomagmatic
 1394 eruption of Okmok Volcano, Aleutian Islands, Alaska: Chronology, deposits,

1395 and landform changes. Technical Report; Alaska Division of Geological and
1396 Geophysical Surveys; 2015.

1397 Larsen J, Śliwiński M, Nye C, Cameron C, Schaefer J. The 2008 eruption of
1398 Okmok Volcano, Alaska: Petrological and geochemical constraints on the sub-
1399 surface magma plumbing system. *Journal of Volcanology and Geothermal Re-*
1400 *search* 2013;264:85–106. doi:[http://dx.doi.org/10.1016/j.jvolgeores.](http://dx.doi.org/10.1016/j.jvolgeores.2013.07.003)
1401 2013.07.003.

1402 Le Pennec JL, Mothes P, Hall M, Ramon P, Ruiz G. Maximum and minimum
1403 volume estimates of an ash fall layer from the August 2001 eruption of Mt
1404 Tungurahua (Ecuador) 2002;:371–4.

1405 Le Pennec JL, Ruiz G, Ramon P, Palacios E, Mothes P, Yepes H. Impact
1406 of tephra falls on Andean communities: The influences of eruption size and
1407 weather conditions during the 1999–2001 activity of Tungurahua volcano,
1408 Ecuador. *Journal of Volcanology and Geothermal Research* 2012;217:91–103.
1409 doi:<http://dx.doi.org/10.1016/j.jvolgeores.2011.06.011>.

1410 Lucic G, Berg AS, Stix J. Water-rich and volatile-undersaturated mag-
1411 mas at Hekla volcano, Iceland. *Geochemistry, Geophysics, Geosystems*
1412 2016;17(8):3111–30. doi:10.1002/2016GC006336.

1413 Luhr JF, Carmichael IS, Varekamp JC. The 1982 eruptions of El Chichón
1414 volcano, Chiapas, Mexico: Mineralogy and petrology of the anhydrite-bearing
1415 pumices. *Journal of Volcanology and Geothermal Research* 1984;23(12):69 –
1416 108. doi:10.1016/0377-0273(84)90057-X.

1417 Macedonio G, Costa A, Folch A. Uncertainties in volcanic plume modeling: A
1418 parametric study using FPLUME. *Journal of Volcanology and Geothermal*
1419 *Research* 2016;doi:10.1016/j.jvolgeores.2016.03.016.

1420 Maeno F, Nagai M, Nakada S, Burden R, Engwell S, Suzuki Y, Kaneko T. Con-
1421 straining tephra dispersion and deposition from three subplinian explosions

1422 in 2011 at Shinmoedake volcano, Kyushu, Japan. *Bulletin of Volcanology*
1423 2014;76(6):823. doi:10.1007/s00445-014-0823-9.

1424 Mahesh K. The interaction of jets with crossflow. *Annual review of fluid me-*
1425 *chanics* 2013;45:379–407. doi:10.1146/annurev-fluid-120710-101115.

1426 Major JJ, Lara LE. Overview of Chaitén volcano, Chile, and its 2008-2009 erup-
1427 tion. *Andean Geology* 2013;40(2):196–215. doi:10.5027/andgeoV40n2-a01.

1428 Malik N. The December 24, 2006 eruption of Bezymyannyi volcano, Kam-
1429 chatka. *Journal of Volcanology and Seismology* 2011;5(4):268. doi:10.1134/
1430 S0742046311040051.

1431 Mankowski L, Riley C, Rose W, McGimsey R, Ernst G. Mapping Ash Grain-
1432 Size Distribution from the August 18, 1992 Eruption of Mt. Spurr. In: AGU
1433 Fall Meeting Abstracts. 2001. .

1434 Marchese F, Falconieri A, Pergola N, Tramutoli V. A retrospective analysis
1435 of the Shinmoedake (Japan) eruption of 26–27 January 2011 by means of
1436 Japanese geostationary satellite data. *Journal of Volcanology and Geothermal*
1437 *Research* 2014;269:1–13. doi:http://dx.doi.org/10.1016/j.jvolgeores.
1438 2013.10.011.

1439 Martin-Del Pozzo A, González-Morán T, Espinasa-Pereña R, Butron M, Reyes
1440 M. Characterization of the recent ash emissions at Popocatepetl Volcano,
1441 Mexico. *Journal of Volcanology and Geothermal Research* 2008;170(1):61–75.
1442 doi:10.1016/j.jvolgeores.2007.09.004.

1443 Marzano FS, Lamantea M, Montopoli M, Herzog M, Graf H, Cimini D. Mi-
1444 crowave remote sensing of the 2011 plinian eruption of the Grímsvötn Ice-
1445 landic volcano. *Remote sensing of Environment* 2013;129:168–84. doi:http:
1446 //dx.doi.org/10.1016/j.rse.2012.11.005.

1447 Mastin L. Testing the accuracy of a 1-D volcanic plume model in estimat-
1448 ing mass eruption rate. *Journal of Geophysical Research: Atmospheres*
1449 2014;119(5):2474–95. doi:10.1002/2013JD020604.

1450 Mastin L, Guffanti M, Servranckx R, Webley P, Barsotti S, Dean K, Durant
1451 A, Ewert J, Neri A, Rose W, et al. A multidisciplinary effort to assign re-
1452 alistic source parameters to models of volcanic ash-cloud transport and dis-
1453 persion during eruptions. *Journal of Volcanology and Geothermal Research*
1454 2009;186(1):10–21. doi:10.1016/j.jvolgeores.2009.01.008.

1455 Mastin LG. A user-friendly one-dimensional model for wet volcanic plumes. *Geo-*
1456 *chemistry, Geophysics, Geosystems* 2007;8(3). doi:10.1029/2006GC001455.

1457 Mastin LG, Schwaiger H, Schneider DJ, Wallace KL, Schaefer J, Denlinger
1458 RP. Injection, transport, and deposition of tephra during event 5 at redoubt
1459 volcano, 23 march, 2009. *Journal of Volcanology and Geothermal Research*
1460 2013;259:201–13. doi:10.1016/j.jvolgeores.2012.04.025.

1461 Matoza RS, Hedlin MA, Garcés MA. An infrasound array study of Mount St.
1462 Helens. *Journal of Volcanology and Geothermal Research* 2007;160(3):249–62.
1463 doi:10.1016/j.jvolgeores.2006.10.006.

1464 Matson M. The 1982 El Chichon volcano eruptionsa satellite perspective. *Jour-*
1465 *nal of Volcanology and Geothermal Research* 1984;23(1-2):1–10. doi:http:
1466 //dx.doi.org/10.1016/0377-0273(84)90054-4.

1467 McGimsey RG, Neal CA, Riley CM. Areal distribution, thickness, mass, volume,
1468 and grain size of tephra-fall deposits from the 1992 eruptions of Crater Peak
1469 vent, Mt. Spurr volcano, Alaska. Technical Report; US Geological Survey;
1470 2001.

1471 Meinel MP, Meinel AB. Late twilight glow of the ash stratum from the eruption
1472 of Agung volcano. *Science* 1963;142(3592):582–3. doi:10.1126/science.142.
1473 3592.582.

1474 Melson W, Allan J, Jerez D, Nelen J, Calvache M, Williams S, Fournelle
1475 J, Perfit M. Water contents, temperatures and diversity of the magmas
1476 of the catastrophic eruption of Nevado del Ruiz, Colombia, November 13,

1477 1985. *Journal of Volcanology and Geothermal Research* 1990;41(1-4):97–126.
1478 doi:[http://dx.doi.org/10.1016/0377-0273\(90\)90085-T](http://dx.doi.org/10.1016/0377-0273(90)90085-T).

1479 Métrich N, Allard P, Spilliaert N, Andronico D, Burton M. 2001 flank eruption
1480 of the alkali-and volatile-rich primitive basalt responsible for Mount Etna’s
1481 evolution in the last three decades. *Earth and Planetary Science Letters*
1482 2004;228(1):1–17. doi:<http://dx.doi.org/10.1016/j.epsl.2004.09.036>.

1483 Miller T, Chouet B. The 1989–1990 eruptions of Redoubt Volcano: an intro-
1484 duction. *Journal of Volcanology and Geothermal Research* 1994;62(1-4):1–10.
1485 doi:[http://dx.doi.org/10.1016/0377-0273\(94\)90025-6](http://dx.doi.org/10.1016/0377-0273(94)90025-6).

1486 Moiseenko K, Malik N. Estimates of total ash content from 2006 and 2009 explo-
1487 sion events at Bezymianny volcano with use of a regional atmospheric model-
1488 ing system. *Journal of Volcanology and Geothermal Research* 2014;270:53–75.
1489 doi:<http://dx.doi.org/10.1016/j.jvolgeores.2013.11.016>.

1490 Moiseenko K, Malik N. Reconstruction of the ashfall at Bezymyanny volcano
1491 during the eruption of December 24, 2006 by using a mesoscale model of the
1492 atmospheric transport of ash particles. *Izvestiya, Atmospheric and Oceanic*
1493 *Physics* 2015;51(6):585–98. doi:10.1134/S0001433815050072.

1494 Morton B. Buoyant plumes in a moist atmosphere. *Journal of Fluid Mechanics*
1495 1957;2(02):127–44. doi:10.1017/S0022112057000038.

1496 Morton BR, Taylor G, Turner JS. Turbulent gravitational convection from main-
1497 tained and instantaneous sources. *Proceedings of the Royal Society of Lon-*
1498 *don A: Mathematical, Physical and Engineering Sciences* 1956;234(1196):1–
1499 23. doi:10.1098/rspa.1956.0011.

1500 Mossop S. Volcanic dust collected at an altitude of 20 km. *Nature*
1501 1964;203(4947):824–7. doi:10.1038/203824a0.

1502 Moune S, Sigmarsson O, Thordarson T, Gauthier PJ. Recent volatile evolution
1503 in the magmatic system of Hekla volcano, Iceland. *Earth and Planetary Sci-*

1504 ence Letters 2007;255(3):373–89. doi:[http://dx.doi.org/10.1016/j.epsl.](http://dx.doi.org/10.1016/j.epsl.2006.12.024)
1505 2006.12.024.

1506 Moxey L. A complete space-based synopsis of eruption dynamics: the 2002
1507 eruption of Reventador Volcano, Ecuador. Master’s thesis; 2005.

1508 Muppidi S, Mahesh K. Direct numerical simulation of passive scalar transport
1509 in transverse jets. *Journal of Fluid Mechanics* 2008;598:335–60. doi:10.1017/
1510 S0022112007000055.

1511 Murrow P, Rose W, Self S. Determination of the total grain size distribution
1512 in a vulcanian eruption column, and its implications to stratospheric aerosol
1513 perturbation. *Geophysical Research Letters* 1980;7(11):893–6. doi:10.1029/
1514 GL007i011p00893.

1515 Myers M, Geist D, Rowe M, Harpp K, Wallace P, Dufek J. Replenishment of
1516 volatile-rich mafic magma into a degassed chamber drives mixing and eruption
1517 of Tungurahua volcano. *Bulletin of Volcanology* 2014;76(11):872. doi:10.
1518 1007/s00445-014-0872-0.

1519 Nakada S, Matsushima T, Yoshimoto M, Sugimoto T, Kato T, Watanabe T,
1520 Chong R, Camacho JT. Geological aspects of the 2003–2004 eruption of
1521 Anatahan volcano, Northern Mariana Islands. *Journal of volcanology and*
1522 *geothermal research* 2005a;146(1):226–40. doi:10.1016/j.jvolgeores.2004.
1523 10.023.

1524 Nakada S, Nagai M, Kaneko T, Nozawa A, Suzuki-Kamata K. Chronology
1525 and products of the 2000 eruption of Miyakejima volcano, Japan. *Bulletin of*
1526 *Volcanology* 2005b;67(3):205–18. doi:10.1007/s00445-004-0404-4.

1527 Nakada S, Nagai M, Kaneko T, Suzuki Y, Maeno F. The outline of the 2011
1528 eruption at Shinmoe-dake (Kirishima), Japan. *Earth, planets and space*
1529 2013;65(6):475–88. doi:10.5047/eps.2013.03.016.

1530 Naranjo J, Sigurdsson H, Carey S, Fritz W. Eruption of the Nevada del Ruiz
1531 volcano, Colombia, on 13 November 1985: tephra fall and lahars. *Science*
1532 1986;233:961–4. doi:10.1126/science.233.4767.961.

1533 Neal C, McGimsey R, Gardner C, Harbin M, Nye C, Keith T. Tephra-fall de-
1534 posits from the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska;
1535 a preliminary report on distribution, stratigraphy, and composition. *US Geol*
1536 *Surv Bull* 1995;2139:65–79.

1537 Newhall CG, Daag AS, Delfin F, Hoblitt RP, McGeehin J, Pallister JS, Regal-
1538 ado M, Rubin M, Tubianosa BS, Tamayo R, et al. Eruptive history of Mount
1539 Pinatubo. *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philip-*
1540 *pines: Philippine Institute of Volcanology and Seismology and University of*
1541 *Washington* 1996;:165–95.

1542 Nye C, Keith T, Eichelberger J, Miller T, McNutt S, Moran S, Schneider
1543 D, Dehn J, Schaefer J. The 1999 eruption of Shishaldin Volcano, Alaska:
1544 monitoring a distant eruption. *Bulletin of volcanology* 2002;64(8):507–19.
1545 doi:10.1007/s00445-002-0225-2.

1546 Oddsson B, Gudmundsson MT, Larsen G, Karlsdóttir S. Monitoring of the
1547 plume from the basaltic phreatomagmatic 2004 Grímsvötn eruption applica-
1548 tion of weather radar and comparison with plume models. *Bulletin of vol-*
1549 *canology* 2012;74(6):1395–407. doi:10.1007/s00445-012-0598-9.

1550 Paladio-Melosantos MLO, Solidum RU, Scott WE, Quiambao RB, Umbal JV,
1551 Rodolfo KS, Tubianosa BS, Delos Reyes P, Alonso RA, Ruelo HB. Tephra
1552 falls of the 1991 eruptions of Mount Pinatubo. *Fire and mud, eruptions and*
1553 *lahars of Mount Pinatubo, Philippines: Philippine Institute of Volcanology*
1554 *and Seismology and University of Washington* 1996;:513–35.

1555 Pallister JS, Trusdell FA, Brownfield IK, Siems DF, Budahn JR, Sutley SF. The
1556 2003 phreatomagmatic eruptions of Anatahan volcanotextural and petrologic
1557 features of deposits at an emergent island volcano. *Journal of Volcanology*

1558 and Geothermal Research 2005;146(1):208–25. doi:10.1016/j.jvolgeores.
1559 2004.11.036.

1560 Parra R, Bernard B, Narv  ez D, Pennec JLL, Hasselle N, Folch A. Eruption
1561 source parameters for forecasting ash dispersion and deposition from vulca-
1562 nian eruptions at Tungurahua volcano: Insights from field data from the july
1563 2013 eruption. Journal of Volcanology and Geothermal Research 2016;309:1
1564 – 13. doi:http://dx.doi.org/10.1016/j.jvolgeores.2015.11.001.

1565 Petersen G, Bjornsson H, Arason P, L  wis Sv. Two weather radar time
1566 series of the altitude of the volcanic plume during the May 2011 erup-
1567 tion of Gr  msv  tn, Iceland. Earth System Science Data 2012;4(1):121–7.
1568 doi:10.5194/essd-4-121-2012.

1569 Pistolesi M, Cioni R, Bonadonna C, Elissondo M, Baumann V, Bertagnini
1570 A, Chiari L, Gonzales R, Rosi M, Francalanci L. Complex dynamics of
1571 small-moderate volcanic events: the example of the 2011 rhyolitic Cord  n
1572 Caulle eruption, Chile. Bulletin of Volcanology 2015;77(1):3. doi:10.1007/
1573 s00445-014-0898-3.

1574 Portnyagin MV, Hoernle K, Mironov NL. Contrasting compositional trends
1575 of rocks and olivine-hosted melt inclusions from Cerro Negro volcano (Cen-
1576 tral America): implications for decompression-driven fractionation of hy-
1577 drous magmas. International Journal of Earth Sciences 2014;103(7):1963–82.
1578 doi:10.1007/s00531-012-0810-3.

1579 Prata A, Siems S, Manton M. Quantification of volcanic cloud top heights and
1580 thicknesses using A-train observations for the 2008 Chait  n eruption. Journal
1581 of Geophysical Research: Atmospheres 2015;120(7):2928–50. doi:10.1002/
1582 2014JD022399.

1583 Pyle DM. The thickness, volume and grainsize of tephra fall deposits. Bulletin
1584 of Volcanology 1989;51(1):1–15. doi:10.1007/BF01086757.

1585 Reckziegel F, Bustos E, Mingari L, Báez W, Villarosa G, Folch A, Collini E,
1586 Viramonte J, Romero J, Osoreo S. Forecasting volcanic ash dispersal and
1587 coeval resuspension during the April–May 2015 Calbuco eruption. *Journal of*
1588 *Volcanology and Geothermal Research* 2016;321:44–57. doi:[http://dx.doi.](http://dx.doi.org/10.1016/j.jvolgeores.2016.04.033)
1589 [org/10.1016/j.jvolgeores.2016.04.033](http://dx.doi.org/10.1016/j.jvolgeores.2016.04.033).

1590 Ridolfi F, Puerini M, Renzulli A, Menna M, Toulkeridis T. The magmatic
1591 feeding system of El Reventador volcano (Sub-Andean zone, Ecuador) con-
1592 strained by texture, mineralogy and thermobarometry of the 2002 erupted
1593 products. *Journal of Volcanology and Geothermal Research* 2008;176(1):94 –
1594 106. doi:10.1016/j.jvolgeores.2008.03.003.

1595 Robock A. Volcanic eruptions and climate. *Reviews of Geophysics* 2000;38:191–
1596 219. doi:10.1029/1998RG000054.

1597 Roggensack K, Hervig RL, McKnight SB, Williams SN. Explosive basaltic vol-
1598 canism from Cerro Negro volcano: Influence of volatiles on eruptive style.
1599 *Science* 1997;277(5332):1639–42. doi:10.1126/science.277.5332.1639.

1600 Romero J, Keller W, Diaz-Alvarado J, Polacci M, Inostroza M. The 3 March
1601 2015 eruption of Villarrica volcano, Southern Andes of Chile: Overview of
1602 deposits and impacts. 2016a. doi:10.13140/RG.2.1.3575.1286.

1603 Romero J, Morgavi D, Arzilli F, Daga R, Caselli A, Reckziegel F, Viramonte
1604 J, Díaz-Alvarado J, Polacci M, Burton M, et al. Eruption dynamics of the
1605 22–23 april 2015 Calbuco volcano (Southern Chile): Analyses of tephra fall
1606 deposits. *Journal of Volcanology and Geothermal Research* 2016b;317:15–29.
1607 doi:<http://dx.doi.org/10.1016/j.jvolgeores.2016.02.027>.

1608 Rose W, Bonis S, Stoiber R, Keller M, Bickford T. Studies of volcanic
1609 ash from two recent Central American eruptions. *Bulletin of Volcanology*
1610 1973;37(3):338–64. doi:10.1007/BF02597633.

1611 Rose W, Gu Y, Watson I, Yu T, Blut G, Prata A, Krueger A, Krotkov N, Carn S,
1612 Fromm M, et al. The February–March 2000 eruption of Hekla, Iceland from

1613 a satellite perspective. *Volcanism and the Earth's Atmosphere* 2003;:107–
1614 32doi:10.1029/139GM07.

1615 Rose W, Self S, Murrow P, Bonadonna C, Durant A, Ernst G. Nature and sig-
1616 nificance of small volume fall deposits at composite volcanoes: Insights from
1617 the October 14, 1974 Fuego eruption, Guatemala. *Bulletin of Volcanology*
1618 2008;70(9):1043–67. doi:10.1007/s00445-007-0187-5.

1619 Rose WI, Anderson AT, Woodruff LG, Bonis SB. The October 1974 basaltic
1620 tephra from Fuego volcano: Description and history of the magma body.
1621 *Journal of Volcanology and Geothermal Research* 1978;4(1):3 – 53. doi:10.
1622 1016/0377-0273(78)90027-6.

1623 Ruprecht P, Bachmann O. Pre-eruptive reheating during magma mixing at
1624 Quizapu volcano and the implications for the explosiveness of silicic arc vol-
1625 canoes. *Geology* 2010;38(10):919–22. doi:10.1130/G31110.1.

1626 Rybin A, Chibisova M, Webley P, Steensen T, Izbekov P, Neal C, Real-
1627 muto V. Satellite and ground observations of the June 2009 eruption of
1628 Sarychev Peak volcano, Matua Island, Central Kuriles. *Bulletin of volcanol-
1629 ogy* 2011;73(9):1377–92. doi:10.1007/s00445-011-0481-0.

1630 Rybin A, Degterev A, Ganzey K, Chibisova M, Razjigaeva N. The Eruptions of
1631 Sarychev Peak Volcano, Kurile Arc: Particularities of Activity and Influence
1632 on the Environment; INTECH Open Access Publisher.

1633 Sadofsky S, Portnyagin M, Hoernle K, van den Bogaard P. Subduction cycling
1634 of volatiles and trace elements through the Central American volcanic arc:
1635 evidence from melt inclusions. *Contributions to Mineralogy and Petrology*
1636 2008;155(4):433–56. doi:10.1007/s00410-007-0251-3.

1637 Saito G, Morishita Y, Shinohara H. Magma plumbing system of the 2000 erup-
1638 tion of Miyakejima volcano, Japan, deduced from volatile and major com-
1639 ponent contents of olivine-hosted melt inclusions. *Journal of Geophysical
1640 Research: Solid Earth* 2010;115(B11). doi:10.1029/2010JB007433.

1641 Samaniego P, Eissen J, Le Pennec J, Robin C, Hall M, Mothes P, Chavrit
 1642 D, Cotten J. Pre-eruptive physical conditions of El Reventador volcano
 1643 (Ecuador) inferred from the petrology of the 2002 and 2004–05 eruptions.
 1644 Journal of Volcanology and Geothermal Research 2008;176(1):82–93. doi:10.
 1645 1016/j.jvolgeores.2008.03.004.

1646 Sarna-Wojcicki AM, Shipley S, Waitt RB, Dzurisin D, et al. The 1980 Eruptions
 1647 of Mount St. Helens, Washington; U.S. Dept. of the Interior, U.S. Geological
 1648 Survey; volume 1250. p. 577–600.

1649 Scaillet B, Evans BW. The 15 June 1991 eruption of Mount Pinatubo. I. phase
 1650 equilibria and pre-eruption P – T – fO_2 – fH_2O conditions of the dacite magma.
 1651 Journal of Petrology 1999;40(3):381–411. doi:10.1093/petroj/40.3.381.

1652 Scasso RA, Corbella H, Tiberi P. Sedimentological analysis of the tephra from
 1653 the 12–15 August 1991 eruption of Hudson volcano. Bulletin of Volcanology
 1654 1994;56(2):121–32. doi:10.1007/BF00304107.

1655 Schneider DJ, Rose WI, Coke LR, Bluth GJ, Sprod IE, Krueger AJ. Early evo-
 1656 lution of a stratospheric volcanic eruption cloud as observed with TOMS and
 1657 AVHRR. Journal of Geophysical Research: Atmospheres 1999;104(D4):4037–
 1658 50. doi:10.1029/1998JD200073.

1659 Scollo S, Del Carlo P, Coltelli M. Tephra fallout of 2001 Etna flank erup-
 1660 tion: analysis of the deposit and plume dispersion. Journal of Volcanology
 1661 and Geothermal Research 2007;160(1):147–64. doi:http://dx.doi.org/10.
 1662 1016/j.jvolgeores.2006.09.007.

1663 Scott Wand McGimsey R. Character, mass, distribution, and origin of tephra-
 1664 fall deposits of the 1989–1990 eruption of Redoubt Volcano, south-central
 1665 Alaska. Journal of Volcanology and Geothermal Research 1994;62(1-4):251–
 1666 72. doi:http://dx.doi.org/10.1016/0377-0273(94)90036-1.

1667 Scott WE, Sherrod DR, Gardner CA. Overview of the 2004 to 2006, and contin-
 1668 uing, eruption of Mount St. Helens, Washington. In: A Volcano Rekindled:

1669 The Renewed Eruption of Mount St. Helens, 2004–2006. US Geological Sur-
1670 vey; volume 1750; 2008. p. 3–22.

1671 Self S, Rampino M. The 1963/1964 eruption of Agung volcano (Bali, In-
1672 donesia. *Bulletin of Volcanology* 2012;74(6):1521–1536. doi:10.1007/
1673 s00445-012-0615-z.

1674 SERNAGEOMIN . Informe de Resumen Crisis Volcán Villarrica Febrero-Marzo
1675 2015. Technical Report; Servicio Nacional de Geología y Minería; 2015.

1676 Shcherbakov VD, Plechov PY, Izbekov PE, Shipman JS. Plagioclase zoning
1677 as an indicator of magma processes at Bezymianny volcano, Kamchatka.
1678 *Contributions to Mineralogy and Petrology* 2011;162(1):83–99. doi:10.1007/
1679 s00410-010-0584-1.

1680 Shibata T, Kinoshita T. Volcanic aerosol layer formed in the tropical upper
1681 troposphere by the eruption of Mt. Merapi, Java, in november 2010 observed
1682 by the spaceborne lidar CALIOP. *Atmospheric Research* 2016;168:49–56.
1683 doi:http://dx.doi.org/10.1016/j.atmosres.2015.09.002.

1684 Solikhin A, Thouret JC, Liew SC, Gupta A, Sayudi DS, Oehler JF, Kassouk
1685 Z. High-spatial-resolution imagery helps map deposits of the large (VEI 4)
1686 2010 Merapi volcano eruption and their impact. *Bulletin of Volcanology*
1687 2015;77(3):20. doi:10.1007/s00445-015-0908-0.

1688 Sparks RSJ, Bursik M, Carey S, Gilbert J, Glaze L, Sigurdsson H, Woods A.
1689 Volcanic plumes. Wiley, 1997.

1690 Spilliaert N, Allard P, Métrich N, Sobolev A. Melt inclusion record of the con-
1691 ditions of ascent, degassing, and extrusion of volatile-rich alkali basalt during
1692 the powerful 2002 flank eruption of Mount Etna (Italy). *Journal of Geophys-*
1693 *ical Research: Solid Earth* 2006;111(B4). doi:10.1029/2005JB003934.

1694 Steffke A, Fee D, Garces M, Harris A. Eruption chronologies, plume heights
1695 and eruption styles at Tungurahua Volcano: Integrating remote sensing tech-

- 1696 niques and infrasound. *Journal of Volcanology and Geothermal Research*
1697 2010;193(3):143–60.
- 1698 Stelling P, Beget J, Nye C, Gardner J, Devine J, George R. Geology and petrol-
1699 ogy of ejecta from the 1999 eruption of Shishaldin Volcano, Alaska. *Bulletin*
1700 *of Volcanology* 2002;64(8):548–61. doi:10.1007/s00445-002-0229-y.
- 1701 Sulpizio R. Three empirical methods for the calculation of distal vol-
1702 ume of tephra-fall deposits. *Journal of volcanology and geother-*
1703 *mal research* 2005;145(3):315–36. doi:http://dx.doi.org/10.1016/j.
1704 *jvolgeores*.2005.03.001.
- 1705 Surono , Jousset P, Pallister J, Boichu M, Buongiorno MF, Budisantoso A, Costa
1706 F, Andreastuti S, Prata F, Schneider D, Clarisse L, et al. The 2010 explosive
1707 eruption of Java’s Merapi volcano a 100-year event. *Journal of volcanology and*
1708 *geothermal research* 2012;241:121–35. doi:http://dx.doi.org/10.1016/j.
1709 *jvolgeores*.2012.06.018.
- 1710 Survey UG. Mount St. Helens from the 1980 eruption to 2000; 2005. U.S.
1711 Geological Survey Fact Sheet 036-00.
- 1712 Suzuki Y, Iguchi M, Maeno F, Nakada S, Hashimoto A, Shimbori T, Ishii K. 3D
1713 numerical simulations of volcanic plume and tephra dispersal: Reconstruction
1714 of the 2014 Kelud eruption. In: *AGU Fall Meeting Abstracts*. volume 1; 2014.
1715 p. 02. URL: <http://adsabs.harvard.edu/abs/2014AGUFM.V53E..02S>.
- 1716 Suzuki Y, Koyaguchi T. Effects of wind on entrainment in volcanic
1717 plumes. *Journal of Geophysical Research* 2015;120(9):6122–40. doi:10.1002/
1718 2015JB012208.
- 1719 Suzuki Y, Yasuda A, Hokanishi N, Kaneko T, Nakada S, Fujii T. Synerup-
1720 tive deep magma transfer and shallow magma remobilization during the 2011
1721 eruption of Shinmoe-dake, Japan Constraints from melt inclusions and phase
1722 equilibria experiments. *Journal of Volcanology and Geothermal Research*

1723 2013;257:184–204. doi:[http://dx.doi.org/10.1016/j.jvolgeores.2013.](http://dx.doi.org/10.1016/j.jvolgeores.2013.03.017)
1724 03.017.

1725 Suzuki YJ, Koyaguchi T. Numerical determination of the efficiency of entrain-
1726 ment in volcanic eruption columns. *Geophysical Research Letters* 2010;37(5).
1727 doi:10.1029/2009GL042159.

1728 Thorarinsson S. The eruption of Mt. Hekla 1947–1948. *Bulletin of Volcanology*
1729 1950;10(1):157–68. doi:10.1007/BF02596085.

1730 Thorarinsson S, Sigvaldason GE. The Hekla eruption of 1970. *Bulletin of*
1731 *Volcanology* 1972;36(2):269–88. doi:10.1007/BF02596870.

1732 Thordarson T, Hayward C, Hartley M, Sigmarsson O, Höskuldsson Á, Larsen
1733 G. The 14 April–22 May 2010 summit eruption at Eyjafjallajökull volcano,
1734 Iceland: Volatile contents and magma degassing. In: *Geophys. Res. Abstr.*
1735 volume 13; 2011. EGU201112046.

1736 Timmreck C. Modeling the climatic effects of large explosive volcanic eruptions.
1737 *Wiley Interdisciplinary Reviews: Climate Change* 2012;3(6):545–64. doi:10.
1738 1002/wcc.192.

1739 Trusdell FA, Moore RB, Sako M, White RA, Koyanagi SK, Chong R, Camacho
1740 JT. The 2003 eruption of Anatahan volcano, Commonwealth of the North-
1741 ern Mariana Islands: chronology, volcanology, and deformation. *Journal of*
1742 *Volcanology and Geothermal Research* 2005;146(1):184–207. doi:10.1016/j.
1743 jvolgeores.2004.12.010.

1744 Tupper A, Wunderman R. Reducing discrepancies in ground and satellite-
1745 observed eruption heights. *Journal of Volcanology and Geothermal Research*
1746 2009;186(12):22 – 31. doi:[http://dx.doi.org/10.1016/j.jvolgeores.](http://dx.doi.org/10.1016/j.jvolgeores.2009.02.015)
1747 2009.02.015; improved Prediction and Tracking of Volcanic Ash Clouds.

1748 Underwood SJ, Feeley TC, Clynne MA. Hydrogen isotope investigation of
1749 amphibole and glass in dacite magmas erupted in 1980–1986 and 2005 at

1750 Mount St. Helens, Washington. *Journal of Petrology* 2013;54(6):1047–70.
1751 doi:10.1093/petrology/egt005.

1752 Unema J. Water-Magma interaction and plume processes in the 2008 Okmok
1753 Eruption. Master’s thesis; 2001.

1754 Van Eaton AR, Amigo Á, Bertin D, Mastin LG, Giacosa RE, González J,
1755 Valderrama O, Fontijn K, Behnke SA. Volcanic lightning and plume be-
1756 havior reveal evolving hazards during the April 2015 eruption of Calbuco
1757 volcano, Chile. *Geophysical Research Letters* 2016;43(7):3563–71. doi:10.
1758 1002/2016GL068076.

1759 Vernier JP, Fairlie TD, Deshler T, Natarajan M, Knepp T, Foster K, Wienhold
1760 FG, Bedka KM, Thomason L, Trepte C. In situ and space-based observations
1761 of the Kelud volcanic plume: The persistence of ash in the lower stratosphere.
1762 *Journal of Geophysical Research: Atmospheres* 2016;121(18). doi:10.1002/
1763 2016JD025344.

1764 Vidal L, Nesbitt S, Salio P, Osoreo S, Farias C, Rodriguez A, Serra J,
1765 Caranti G. C-Band Dual-Polarization observations of a massive vol-
1766 canic eruption in South America. In: AMS. 2015. URL: [https://ams.confex.com/ams/37RADAR/webprogram/Handout/Paper276312/](https://ams.confex.com/ams/37RADAR/webprogram/Handout/Paper276312/ID276312_AMSRadarConf2015_Vidal_et_al.pdf)
1767 [ID276312_AMSRadarConf2015_Vidal_et_al.pdf](https://ams.confex.com/ams/37RADAR/webprogram/Handout/Paper276312/ID276312_AMSRadarConf2015_Vidal_et_al.pdf).
1768

1769 Voight B. The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retro-
1770 spection. *Journal of Volcanology and Geothermal Research* 1990;42(1-2):151–
1771 88. doi:[http://dx.doi.org/10.1016/0377-0273\(90\)90075-Q](http://dx.doi.org/10.1016/0377-0273(90)90075-Q).

1772 Wallace K, Schaefer J, Coombs M. Character, mass, distribution, and origin
1773 of tephra-fall deposits from the 2009 eruption of Redoubt Volcano, Alaska–
1774 Highlighting the significance of particle aggregation. *Journal of Volcanol-
1775 ogy and Geothermal Research* 2013;259:145–69. doi:[http://dx.doi.org/10.](http://dx.doi.org/10.1016/j.jvolgeores.2012.09.015)
1776 [1016/j.jvolgeores.2012.09.015](http://dx.doi.org/10.1016/j.jvolgeores.2012.09.015).

Wallace KL, Neal CA, McGimsey RG. Timing, distribution, and character of
tephra fall from the 2005–2006 eruption of Augustine volcano. US Geological
Survey Professional Paper 2006;:187–217.

Watt SF, Pyle DM, Mather TA, Martin RS, Matthews NE. Fallout and distribu-
tion of volcanic ash over Argentina following the May 2008 explosive eruption
of chaitén, chile. *Journal of Geophysical Research: Solid Earth* 2009;114(B4).
doi:10.1029/2008JB006219.

Waythomas CF, Scott WE, Prejean SG, Schneider DJ, Izbekov P, Nye CJ.
The 7–8 August 2008 eruption of Kasatochi volcano, central Aleutian Islands,
Alaska. *Journal of Geophysical Research: Solid Earth* 2010;115(B12). doi:10.
1029/2010JB007437.

Webster JD, Mandeville CW, Goldoff B, Coombs ML, Tappen C. Augustine vol-
canothe influence of volatile components in magmas erupted ad 2006 to 2,100
years before present. US Geological Survey Professional Paper 2006;:383–423.

Williams S, Self S. The October 1902 plinian eruption of Santa Maria volcano,
Guatemala. *Journal of Volcanology and Geothermal Research* 1983;16(1-
2):33–56. doi:[http://dx.doi.org/10.1016/0377-0273\(83\)90083-5](http://dx.doi.org/10.1016/0377-0273(83)90083-5).

Wilson L, Sparks R, Huang T, Watkins N. The control of volcanic column
heights by eruption energetics and dynamics. *Journal of Geophysical Re-
search: Solid Earth* 1978;83(B4):1829–36. doi:10.1029/JB083iB04p01829.

Woodhouse M, Hogg A, Phillips J, Sparks RSJ. Interaction between volcanic
plumes and wind during the 2010 Eyjafjallajökull eruption, Iceland. *Journal
of Geophysical Research* 2013;118(1):92–109. doi:10.1029/2012JB009592.

Woodhouse MJ, Hogg AJ, Phillips JC, Rougier JC. Uncertainty analysis of a
model of wind-blown volcanic plumes. *Bulletin of Volcanology* 2015;77(10):1–
28. doi:10.1007/s00445-015-0959-2.

1803 Woods A. Moist convection and the injection of volcanic ash into the atmo-
1804 sphere. *Journal of Geophysical Research: Solid Earth* 1993;98(B10):17627–36.
1805 doi:10.1029/93JB00718.

1806 Woods A. The dynamics of explosive volcanic eruptions. *Review of Geophysics*
1807 1995;33:496–530. doi:10.1029/95RG02096.

1808 Woods AW, Bower SM. The decompression of volcanic jets in a crater
1809 during explosive volcanic eruptions. *Earth and Planetary Science Letters*
1810 1995;131(3):189 – 205. doi:10.1016/0012-821X(95)00012-2.

1811 Wright R, Carn SA, Flynn LP. A satellite chronology of the May–June 2003
1812 eruption of Anatahan volcano. *Journal of Volcanology and Geothermal Re-*
1813 *search* 2005;146(1):102–16. doi:10.1016/j.jvolgeores.2004.10.021.

1814 Yang W, Hwang R. Vertical buoyant jets in a linearly stratified ambient cross-
1815 stream. *Environmental Fluid Mechanics* 2001;.

1816 Zen M, Hadikusumo D. Preliminary report on the 1963 eruption of Mt. Agung
1817 in Bali (Indonesia). *Bulletin Volcanologique* 1964;27(1):269–99. doi:10.1007/
1818 BF02597526.

Table 1: Symbols used in this study. 0-subscript refers to source conditions. For plume properties, symbols with hat refer to properties non-dimensionalized using Equation 16.

	Parameter	Symbol	Unit
Plume	Bulk velocity	u	m.s^{-1}
	Bulk density	ρ	kg.m^{-3}
	Radius	r	m
	Downwind or upwind radius	$r_{down/up}$	m
	Plume asymmetry factor	A_s	—
	Entrainment velocity	u_ϵ	m.s^{-1}
	Radial entrainment parameter	α	—
	Wind entrainment parameter	β	—
	Equivalent entrainment parameter	ϵ	—
	Plume deflection relative to horizontal	θ	rad
	Plume deflection relative to vertical	ϕ	rad
	Plume mean deflection relative to vertical	$\bar{\phi}$	rad
	Bulk Buoyancy	g'	m.s^{-2}
	Plume maximum height	H_{max}	m
	Scaling height from ref	H^{ref}	m
	Jet/plume transition length	l^m	m
	Vertical distance from source	z	m
	Horizontal distance from source	x	m
	Distance from source along centerline	s	m
	Buoyancy flux	f	$\text{m}^4.\text{s}^{-3}$
	Momentum flux	m	$\text{m}^4.\text{s}^{-2}$
	Volume flux	q	$\text{m}^3.\text{s}^{-1}$
	Source temperature	T_0	K
	Source gas content	n_0	wt. %
Atmosphere	Horizontal wind speed	w	m.s^{-1}
	Density	ρ_a	kg.m^{-3}
	Radius	r	m
	Entrainment velocity	u_ϵ	m.s^{-1}
	Horizontal wind speed averaged over plume height	W	m.s^{-1}
	Brunt Väisälä frequency	N	s^{-1}
	Tropopause altitude	H_{tp}	m
	Relative humidity	RH	—
Regime parameters	Velocity ratio	$\mathcal{W}^*$	—
	Richardson number	$\mathcal{R}i$	—
	Gradient Richardson number	$\mathcal{R}i_g$	—
	Wind Richardson number	$\mathcal{R}i^{wind}$	—
	Wind Gradient Richardson number	$\mathcal{R}i_g^{wind}$	—
	Wind Velocity to Pure Plume Velocity Scale Ratio	$\mathcal{V}_0^*$	—
	Wind Gradient to Plume Velocity Gradient Ratio	$\mathcal{T}^*$	—
Constants	Gravity Acceleration of Earth	g	m.s^{-2}
	Specific gas constant	R	$\text{J.kg}^{-1}.\text{K}^{-1}$
	Empirical parameter for the Carazzo et al. (2014) scaling	a_c	—
	Height of the tank (for laboratory experiment)	H_{tank}	m

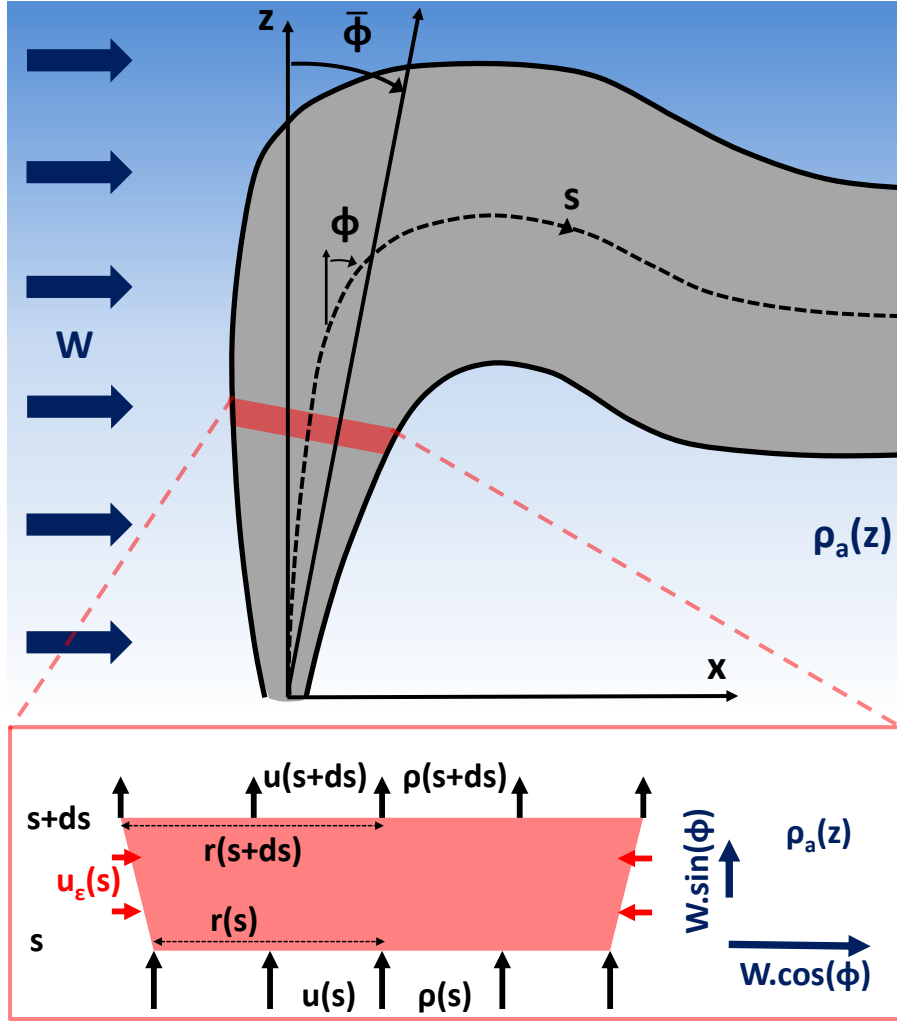


Figure 2: Cartoon of a rising plume (top) and of the control volume (bottom) used to derive conservation Equations. $\bar{\phi} = \frac{1}{H_{max}} \int_0^{H_{max}} \phi dz$ is the mean angle of rise.

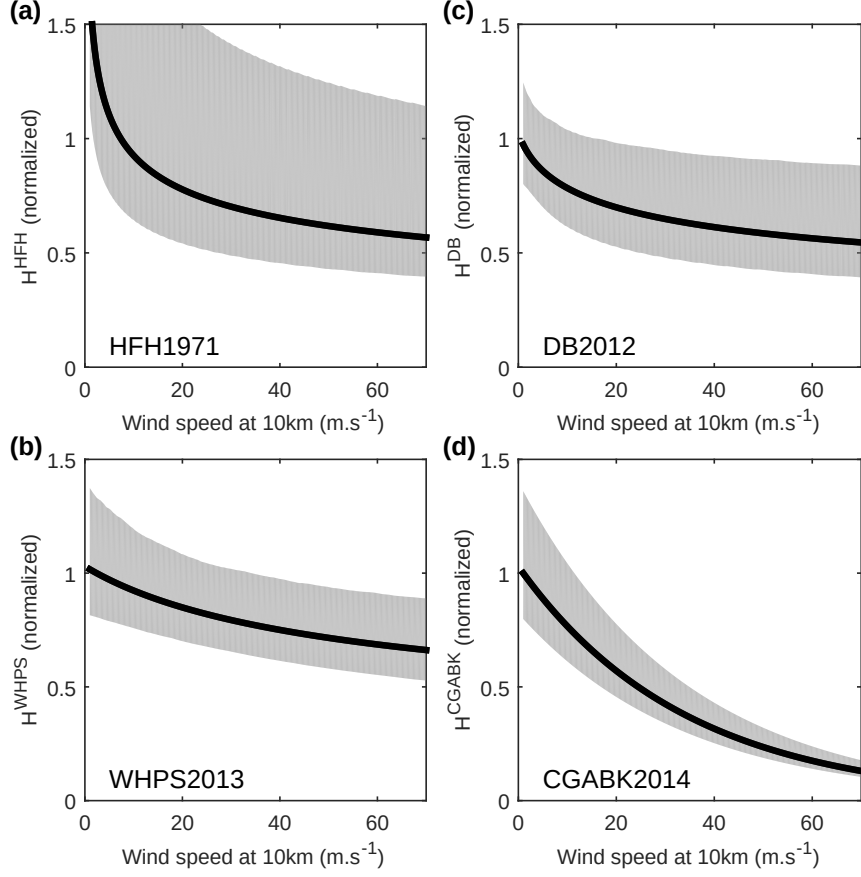


Figure 3: Standardized plume height as a function of the wind speed at 10km. Panels (a), (b), (c) and (d) show height predicted by the Hewett et al. (1971), Degruyter and Bonadonna (2012), Woodhouse et al. (2013) and Carazzo et al. (2014) scalings respectively. All height are normalized using the Morton et al. (1956) scaling with $\alpha = 0.1$. We used $F_0 = 10^7 \text{ m}^4 \text{ s}^{-3}$, $N = 0.015 \text{ s}^{-1}$, $U_0 = 300 \text{ m.s}^{-1}$, and assumed that the wind was linearly increasing with altitude. We use a Monte Carlo method to randomly sample entrainment coefficients α and β and estimate the 95% confidence interval on predicted plume height (shadings). For α (respectively β), we assume a gaussian distribution of mean 0.1 (respectively 0.55) and standard deviation 0.025 (respectively 0.225).

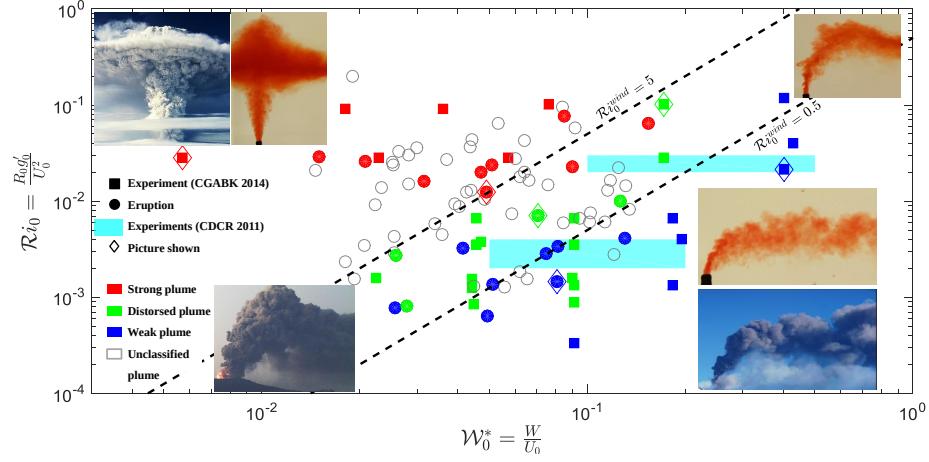


Figure 4: Regime diagram for the Carazzo et al. (2014) experiments (CGABK 2014, squares), volcanic eruptions (Table S2, circles), and Contini et al. (2011) experiments (CDCR 2011, shaded in light blue). $\mathcal{W}_0^*$ and $\mathcal{Ri}_0$ are the x-axis and y-axis respectively (logarithmic scale). Error bars are not shown for clarity. Typical relative error for experiments is $\simeq 10\%$, while errors for natural eruptions are about half an order of magnitude. Red, green, blue and open symbols respectively indicate strong (the umbrella spreads both up- and downwind), distorted (the plume rises above the umbrella, which spreads only downwind), weak (the plume does not rise above the umbrella) and undetermined plume regimes. Two plumes pictures are shown for each regime: one is issued from analog experiments, the other one corresponds to a real eruption: Puyehue-Cordón Caulle (5th June 2011), Eyjafjallajökull (10th May 2010) and Etna (24th November 2006) for the strong, distorted and weak plume regimes respectively. Eruptions or experiments for which pictures are shown are highlighted by a diamond symbol. Dashed lines, defined by empirical critical values of $\mathcal{Ri}_0^{wind}$, show estimated regimes boundaries. Photo of Mt Etna by Luigi Lodato. Photo of Eyjafjallajökull courtesy of Dr. Arason. Photo of Puyehue-Cordón Caulle modified from a picture by air force of Chile/Reuters.

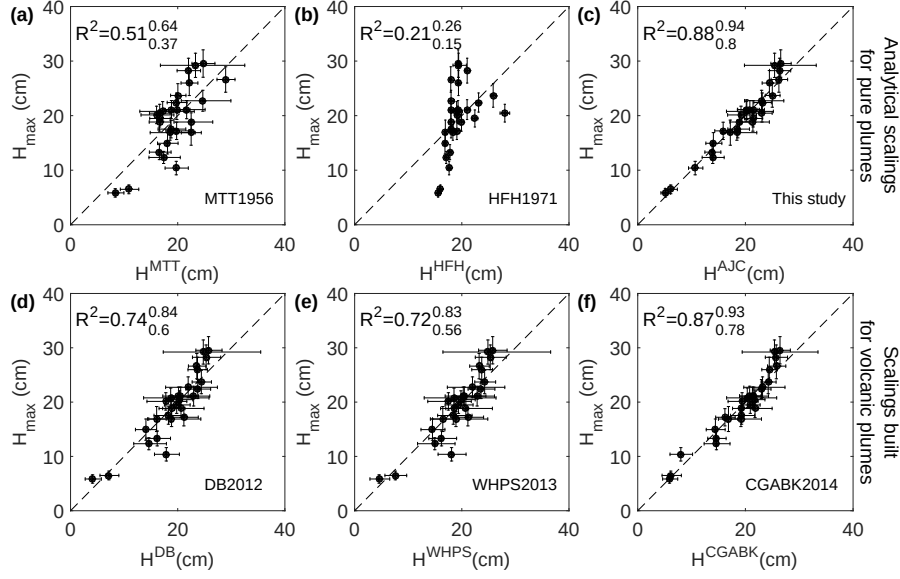


Figure 5: Measured height H_{max} (cm) as a function of scaling heights for the set of analogue experiments from Carazzo et al. (2014). Panels (a)-(f) show the Morton et al. (1956) (MTT1956), Hewett et al. (1971) (HFH1971), our proposed, Degruyter and Bonadonna (2012) (DB2012), Woodhouse et al. (2013) (WHPS2013) and Carazzo et al. (2014) (CGABK2014) scalings respectively. In panels (a)-(c), scalings have been derived analytically for a pure plume model, with different assumptions on the wind speed. In panels (d)-(f), scalings are functional corrections to the Morton et al. (1956) intended to be applied to volcanic plumes. Error bars show the estimated 95% confidence intervals. Black dashed lines show the linear function of slope 1. Determination coefficients are annotated on each graph, with the 95% confidence bounds indicated in subscript/superscript.

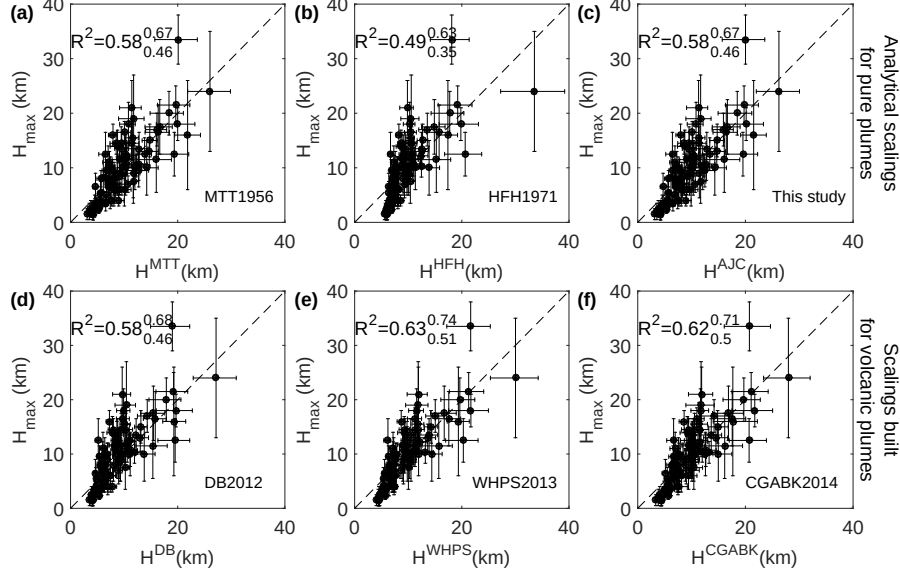


Figure 6: Same as Figure 5, but using data from explosive eruptions instead of analog experiments.

Table 2: Coefficients of the multiple linear regression of the logarithm of the mass eruption rate (in $kg.s^{-1}$) associated, from 1st to 4th row respectively, to the constant term, the logarithm of the plume height (in km), the logarithm of the Brunt-Väisälä frequency (in s^{-1}), and the wind parameter (the logarithm of wind speed in $m.s^{-1}$ for Hewett et al. (1971), dimensionless parameter otherwise). The last row gives the associated coefficient of determination. Coefficients using only the plume height as independent variables (like Mastin (2014)) are indicated in the 8th column (M2014). Subscripts/superscripts indicate the 95% confidence interval.

Coef.	MTT1956	HFH1971	this study	DB2012	WHPS2013	CGABK2014	M2014
C	$7.5^{9.8}_{5.4}$	$6.8^{9.1}_{4.6}$	$7.4^{9.8}_{5.3}$	$7.9^{9.9}_{5.9}$	$7.4^{9.8}_{5.0}$	$6.2^{9.8}_{5.1}$	$2.9^{3.2}_{2.6}$
C_H	$3.4^{3.7}_{3.0}$	$3.4^{3.7}_{3.0}$	$3.4^{3.7}_{3.0}$	$2.7^{3.0}_{2.2}$	$3.8^{4.2}_{3.2}$	$3.5^{3.8}_{3.1}$	$3.6^{3.9}_{3.3}$
C_N	$2.3^{3.4}_{1.2}$	$2.2^{3.3}_{1.1}$	$2.3^{3.4}_{1.2}$	$1.9^{2.9}_{1.0}$	$2.5^{3.7}_{1.4}$	$2.5^{3.6}_{1.4}$	—
C_W	—	$0.5^{0.8}_{0.2}$	$1.1^{3.4}_{-1.2}$	$-0.3^{-0.2}_{-0.4}$	$0.7^{1.3}_{0.2}$	$6.4^{8.7}_{4.5}$	—
R^2	$0.72^{0.77}_{0.66}$	$0.73^{0.78}_{0.66}$	$0.72^{0.77}_{0.65}$	$0.77^{0.81}_{0.72}$	$0.73^{0.79}_{0.66}$	$0.76^{0.81}_{0.69}$	$0.70^{0.76}_{0.64}$

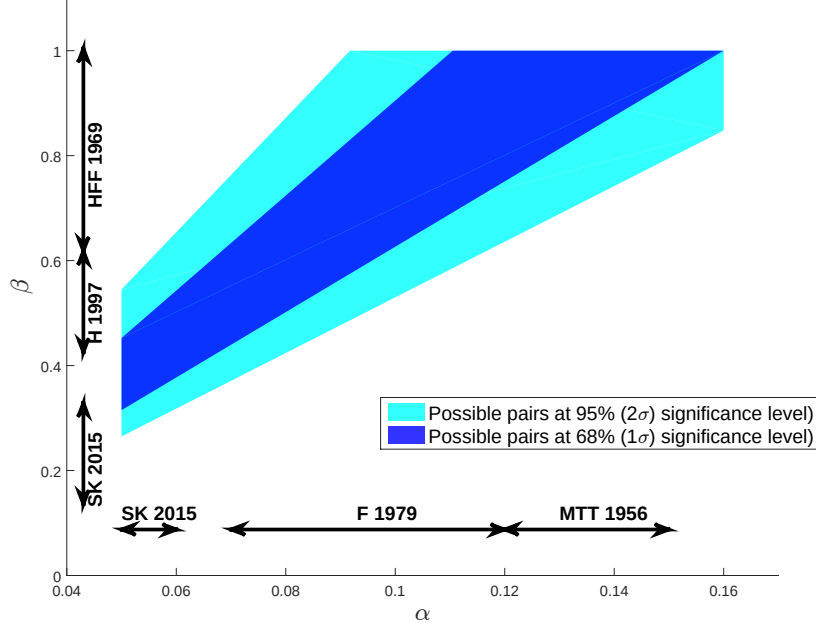


Figure 7: Summary of current constraints on entrainment coefficients. Arrows along the x and y axis show values of α and β calibrated from previous studies. HFF 1969, H 1997, SK 2015, F 1979 and MTT 1956 refer to Hoult et al. (1969), Huq (1997), Suzuki and Koyaguchi (2015), Fischer et al. (1979) and Morton et al. (1956) respectively. Shaded area bounds the values of $\frac{\beta}{\alpha}$ estimated using the Carazzo et al. (2014) dataset and proposed scaling (Equation 24), for 2 levels of significance (68%, blue, and 95%, cyan).

Table S1: Table S1 (available in a separate spreadsheet) contains the buoyancy flux, source velocity, Brunt-Väisälä frequency, crossflow speed, and maximum height for the experiments from the Carazzo et al. (2014) dataset, and their associated uncertainty. Experiments for which the top of the plume was less than 8cm above the bottom of the tank have been excluded.

Table S2: Table S2 (available in a separate spreadsheet) contains eruptive parameters, atmospheric parameters, references and specific comments on the 94 eruptive phases for which we could find independent estimate of the plume height, the erupted mass and the eruption duration.

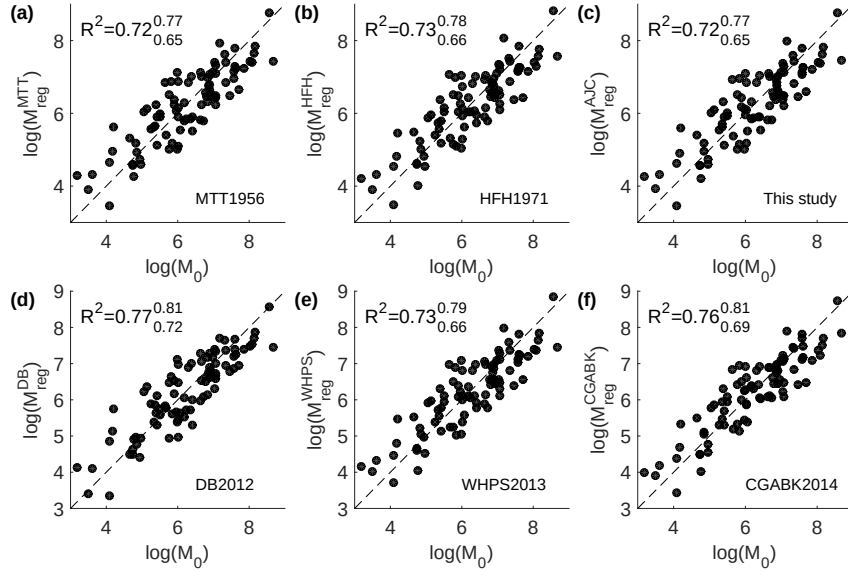


Figure 8: Same as Figure 6, but showing the logarithm of the regressed mass eruption rate using the set of parameters employed in each scaling as independent regression parameters (logarithm of the plume height, Brunt-Väisälä frequency, and wind parameter associated to each scaling), as a function of the logarithm of the measured mass eruption rate. Regression coefficients for each scaling are indicated in Table 2. Error bars are not shown for clarity but are typically about 0.5 (half an order of magnitude).

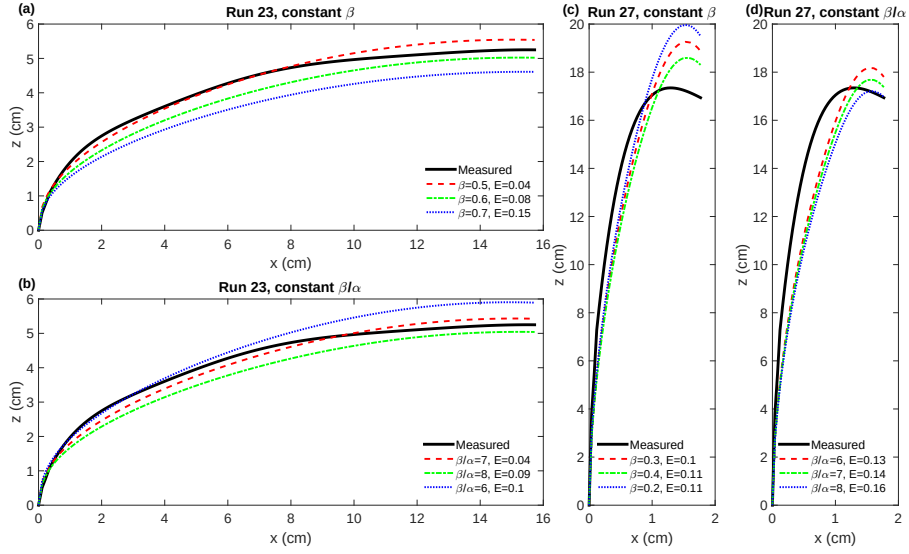


Figure 9: Plume trajectories for experiments 23 (panels (a) and (b), $W_0^* = 4.3 \cdot 10^{-2}$) and 27 (panels (c) and (d), $W_0^* = 3.5 \cdot 10^{-3}$) of the Carazzo et al. (2014) dataset. The thick black line shows measured trajectories. Colored discontinuous lines show trajectories predicted by the Carazzo et al. (2008) buoyant jet model using a constant β (panels (a) and (c)) or a constant $\frac{\beta}{\alpha}$ (panels (b) and (d)). In each case, we show the three values of β or $\frac{\beta}{\alpha}$ for which the measured plume trajectory is best reproduced. The associated relative root mean squared error (E , cf Section 5) is indicated for each modeled trajectory.

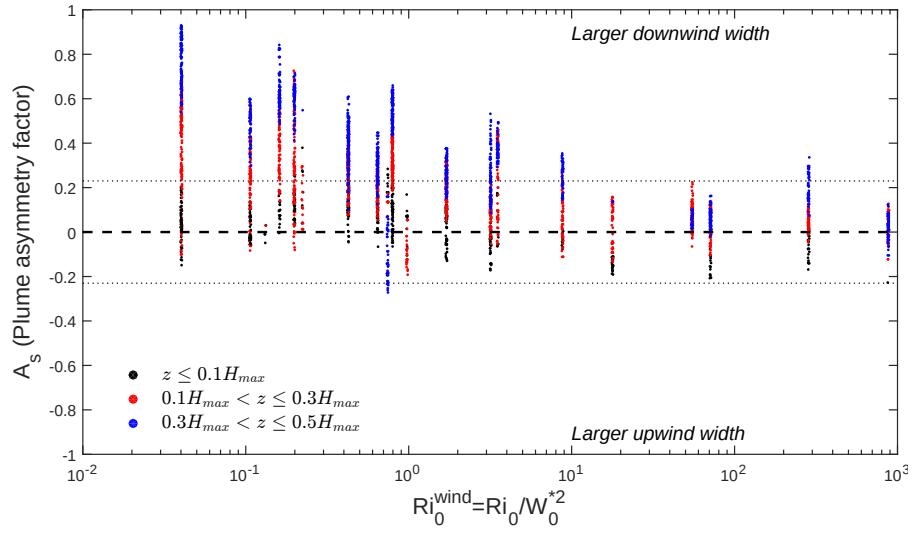


Figure 10: Plume asymmetry factor (A_s , cf Section 5) as a function of the wind Richardson number ($\mathcal{R}i_0^{wind} = \frac{\mathcal{R}i_0}{W_0^{*2}}$) for the Carazzo et al. (2014) experiments. Black, red and blue dots indicate measurements for $z \leq 0.1H_{max}$, $0.1H_{max} < z \leq 0.3H_{max}$ and $0.3H_{max} < z \leq 0.5H_{max}$, respectively. Dashed lines show the maximum absolute value of A_s for the experiment with the lowest $\mathcal{R}i_0^{wind}$. Positive A_s , above the thick dashed line, indicates that the plume upwind width is significantly larger than the plume downwind width, and vice-versa.

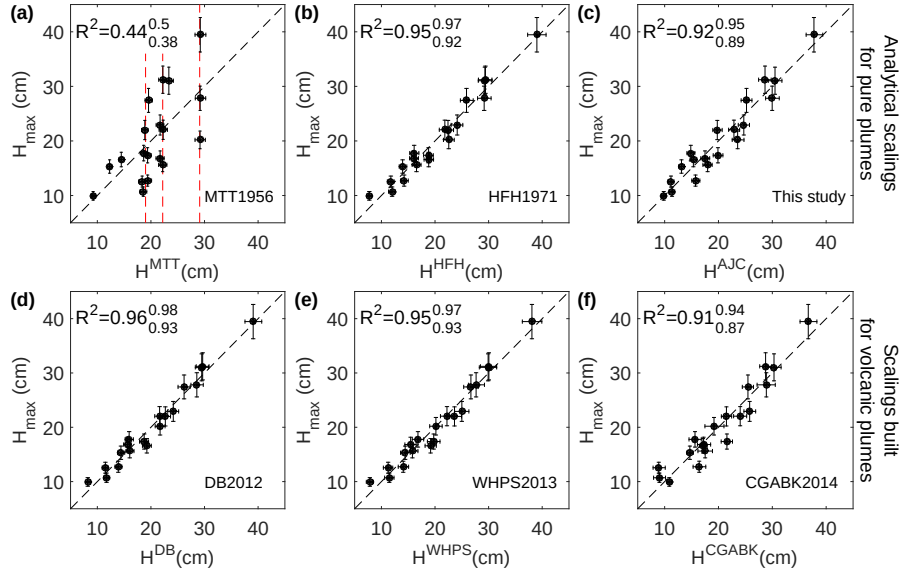


Figure 11: Same as Figure 5, but using laboratory experiments from Contini et al. (2011). Red dashed lines highlight the three main values of H^{MTT} used in these experiments.

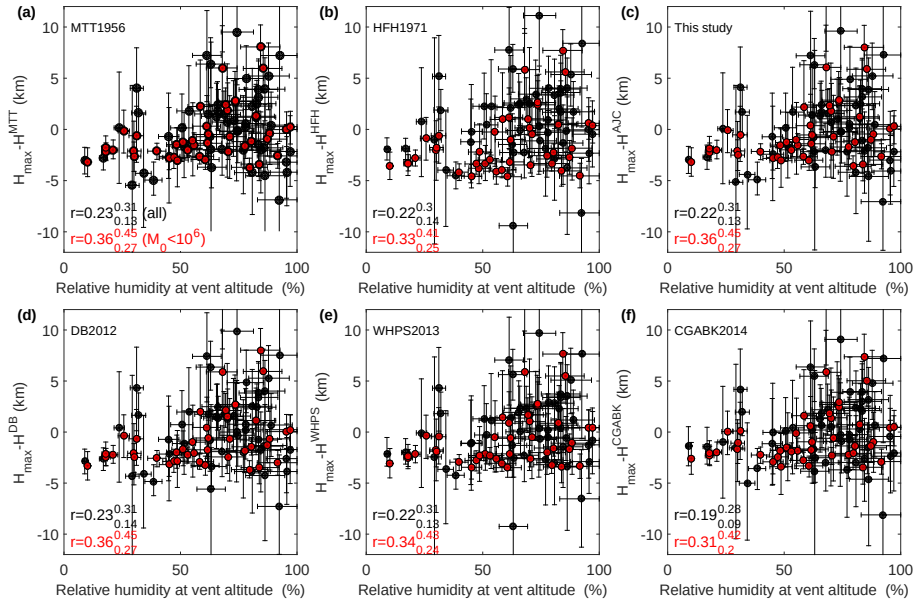


Figure 12: Residual height for each scaling as a function of the atmosphere relative humidity at vent altitude. Red dots show eruptions with $M_0 < 10^6 \text{ kg.s}^{-1}$ which are expected to be more impacted by condensation of entrained water vapor. The correlation coefficient between the residual height and relative humidity across all eruptions (respectively eruptions with $M_0 < 10^6 \text{ kg.s}^{-1}$) is indicated on each panel in black (respectively red).

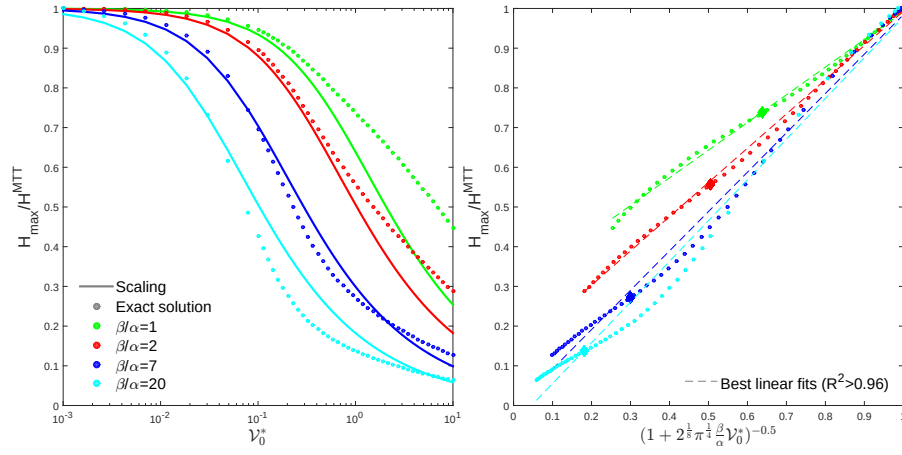


Figure S1: Left: comparison of the numerical solution of the governing Equations 15 H_{max}/H^{MTT} (dots) with the proposed scaling (continuous line, Equation 22) for values of V_0^* between 10^{-3} and 10, and four values of the entrainment coefficients ratio $\frac{\beta}{\alpha}$ labeled with four different colors. Right: numerical solution as a function of the proposed scaling for the entrainment rate for pure plumes (Equation 21). The best linear fit (dashed line) is shown for each ratio ($R^2 > 0.96$). Diamond symbols correspond to $V_0^* = 1$.

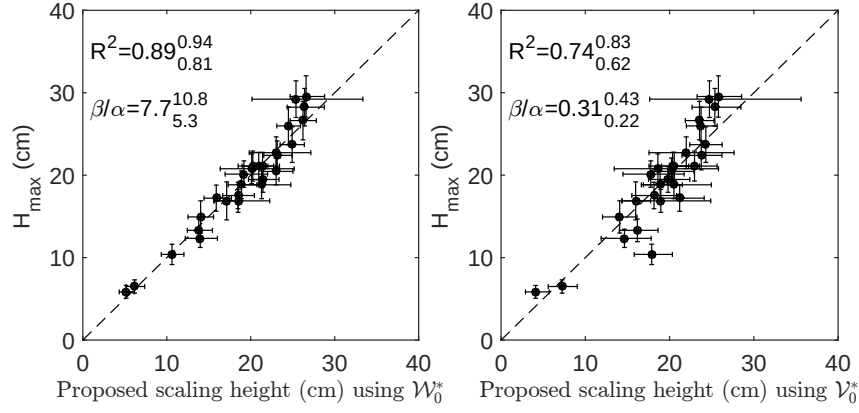


Figure S2: Same as Figure 5, but showing only results for the proposed scaling. In the left panel, the velocity ratio based on the momentum flux ($\mathcal{W}_0^*$) is used to scale the entrainment rate (Equation 24, which is the scaling we discuss in this paper). In the right panel, the velocity ratio based on the buoyancy flux ($\mathcal{V}_0^*$) is used to scale the entrainment rate (Equation 24, which approximates well the numerical solution of governing Equations 15 for pure plumes). The coefficient of determination R^2 and ratio of entrainment coefficients $\frac{\beta}{\alpha}$ found by fitting the scaling to experimental plume height is annotated on each graph. The scaling based on $\mathcal{V}_0^*$ has a lower R^2 (difference significant at the 95% level), and results in values of $\frac{\beta}{\alpha}$ unrealistically low compared to published values of β and α .

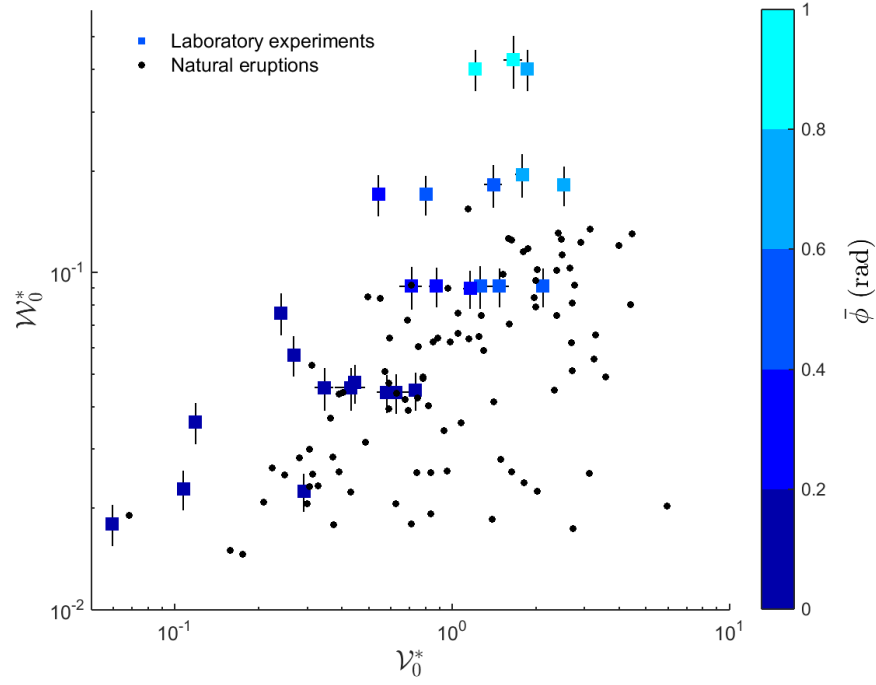


Figure S3: $\mathcal{V}_0^*$ - $\mathcal{W}_0^*$ regime diagram for the Carazzo et al. (2014) experiments (squares) and the natural eruptions (dots) from Table S2. For laboratory experiments, shading shows the mean angle of rise $\bar{\phi}$, which is assumed to be small when deriving the proposed scaling (Section 2). Error bars show 95% confidence intervals and are displayed only for laboratory experiments for clarity. Uncertainty on $\bar{\phi}$ does not exceed 0.05 radians. Uncertainties for natural eruptions are about half an order of magnitude.

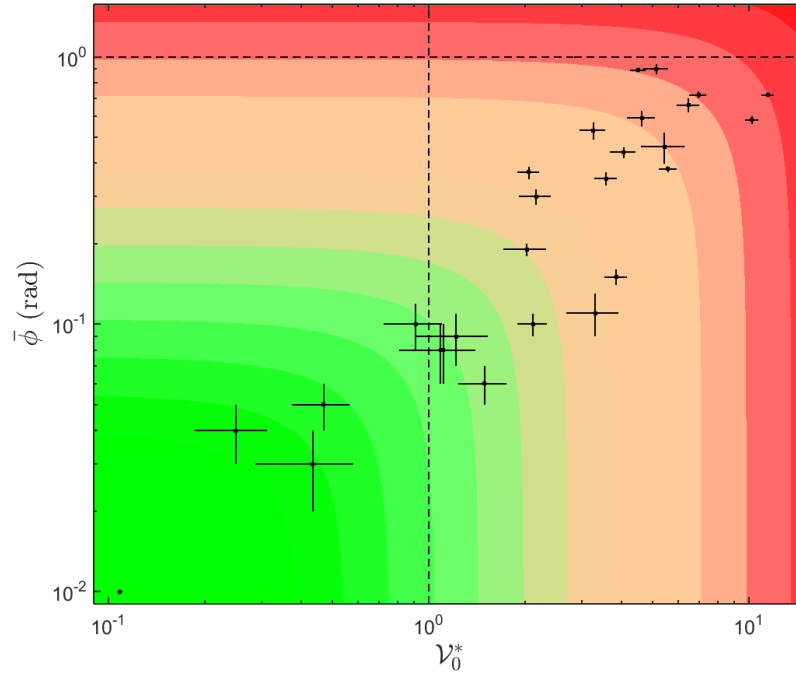


Figure S4: Mean angle of rise $\bar{\phi}$ as a function of $\mathcal{V}_0^*$ for the Carazzo et al. (2014) experiments. In deriving the scaling in Section 2, we assume $\bar{\phi} \ll 1$ and $\mathcal{V}_0^* < 1$. Green shading highlights the parameter space for which both assumptions hold while red shading highlights experiments for which at least one these two assumption is violated.

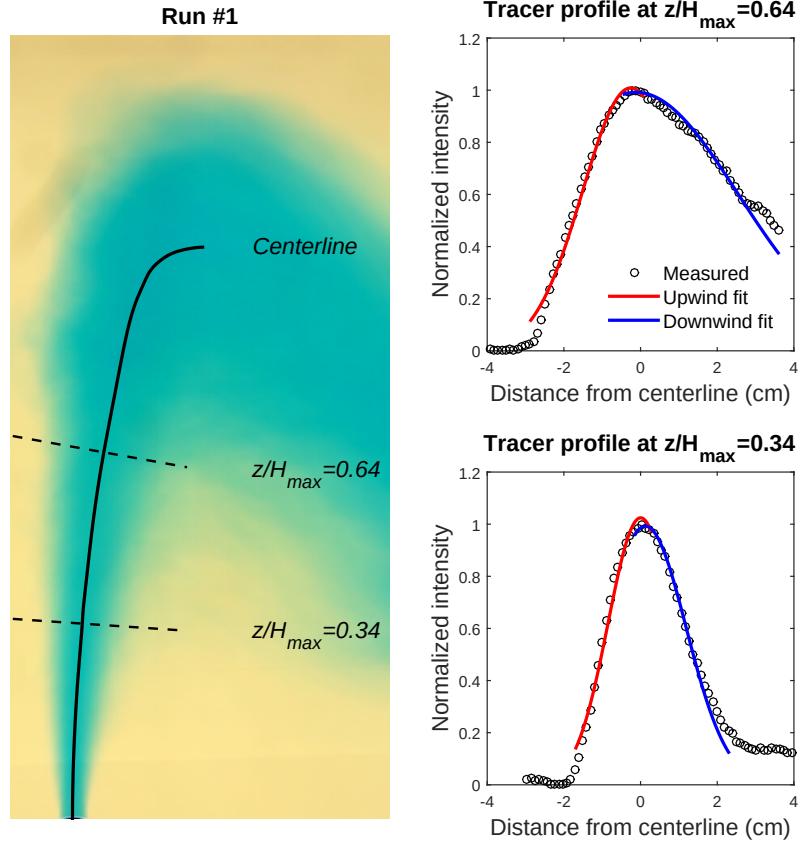


Figure S5: Examples of tracer intensity profiles for the first run of the Carazzo et al. (2014) dataset. The left picture shows the average of 190 video frames recorded over $\simeq 8$ seconds, the plume centerline (where tracer intensity is maximal) and two cross-sections of the plume. The two plots on the right show the tracer intensity profiles corresponding to these two cross-sections (circles). Red and blue lines show gaussian fits of the upwind and downwind halves of the plume, respectively. For the profile measured at $\frac{z}{H_{max}} = 0.64$, the intensity does not decrease below 0.4 at the downwind edge because of the overlap of the ascending and descending parts of the plume apart from the overshoot height. For this reason, we use only profiles measured at $\frac{z}{H_{max}} \leq 0.5$ to measure the plume asymmetry factor in Section 5.