

Tephra Fallout Probabilistic Hazard Maps for Cotopaxi and Guagua Pichincha Volcanoes (Ecuador) With Uncertainty Quantification

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Alessandro Tadini, N. Azzaoui, Olivier Roche, P. Samaniego, B. Bernard, et al.. Tephra Fallout Probabilistic Hazard Maps for Cotopaxi and Guagua Pichincha Volcanoes (Ecuador) With Uncertainty Quantification. Journal of Geophysical Research : Solid Earth, 2022, 127 (2), 10.1029/2021JB022780 . hal-03603654

HAL Id: hal-03603654 https://uca.hal.science/hal-03603654

Submitted on 10 Mar 2022

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1 2	Tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes (Ecuador) with uncertainty quantification										
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14 15	Kev Points:										
16 17	 We develop tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes using the PLUME-MoM/HYSPLIT model 										
18 19	• We incorporate the quantification of the uncertainty on the input parameters, the model, and the occurrence of different eruption types										
20 21	• Our study indicates that full uncertainty quantification is essential in volcanic hazard assessment in order to provide robust information										
22 23 24 25 26 27 28 29	 Index Terms and Keywords 4314 Mathematical and computer modeling, 3275 Uncertainty quantification, 8428 Explosive volcanism, 8488 Volcanic hazards and risks Tephra fallout, volcanic hazard assessment, Cotopaxi, Guagua Pichincha, uncertainty quantification 										
30 31											

32 Abstract

Tephra fallout hazard assessment is undertaken with probabilistic maps that rely on numerical 33 34 models. Regarding maps production, the input parameters of the model (including atmospheric conditions), the physical approximations of the numerical simulations, and the probabilities of 35 occurrence of different eruption types in specific time frames are among the most critical sources 36 37 of uncertainty. We therefore present a tephra fallout hazard assessment study for two active volcanoes (Cotopaxi and Guagua Pichincha) in Ecuador. We utilize PLUME-MoM/HYSPLIT 38 models, and a procedure for uncertainty quantification where: i) the uncertainty on eruptive 39 40 source parameters and eruption type occurrence is quantified through expert elicitation; ii) we implement a new procedure for correlations between the different parameters, and iii) we use 41 correction coefficients to take into account the uncertainty of the numerical model. Maps of 42 exceedance probability given a deposit thickness threshold, and thickness maps given a 43 probability of exceedence, are produced 1) for two eruptive scenarios (sub-plinian and Plinian) 44 and 2) as a combination of these scenarios in case the next eruption will be sub-Plinian or 45 Plinian. These maps are described according to the uncertainty distribution of eruption type 46 occurrence probabilities, considering their 5th percentile, mean, and 95th percentile values. We 47 finally present hazard curves describing exceeding probabilities in 10 sensitive sites within the 48 city of Quito. Additional information includes the areal extent and the population potentially 49 50 affected by different isolines of tephra accumulation. This work indicates that full uncertainty quantification helps in providing more robust scientific information, improving the hazard 51 assessment reliability. 52

53 Plain language summary

We present a tephra fallout (i.e., volcanic ash accumulation on the ground due to sedimentation 54 from volcanic clouds) hazard assessment for two Ecuadorian volcanoes (Cotopaxi and Guagua 55 Pichincha) threatening Quito, the capital city of Ecuador. The novelties of this study are that i) 56 we use coupled models for eruptive column and ash transport and ii) we quantify the main 57 58 sources of uncertainties that normally affect probabilistic hazard maps. In particular, we present probability maps, for which a certain deposit thickness is overcome, and thickness maps, which 59 show the expected thickness for a given probability. For the two volcanoes, the maps are related 60 to the case that a next eruption will be of medium to large size (i.e. sub-Plinian or Plinian). 61 Moreover, we also present hazard curves for 10 sensitive sites within the city of Quito. These 62 curves are used to infer, for each site, the probabilities for a given accumulation of ash. Finally, 63 we show the areal extent and the poupulation potentially affected by different tephra 64 accumulations. Our study points toward the necessity to perform a full uncertainty quantification 65 for volcanic hazard assessment. 66

67 **1 Introduction**

Among the numerous hazards related to volcanic eruptions, tephra fallout is certainly one of the most severe because it may affect large areas (> 100 km²; Blong, 1996) and has a dramatic impact on both human settlements and activities (Brown *et al.*, 2017). While tephra residence in the atmosphere can lead to near-total disruption of air traffic over a vast region (e.g., Eyjafjallajokull 2010 eruption; Budd *et al.*, 2011; Bursik *et al.*, 2009; Folch *et al.*, 2012; Folch & Sulpizio, 2010), tephra accumulation on the ground affects human health (Baxter, 1990; Baxter & Horwell, 2015), buildings stability (Macedonio & Costa, 2012; Spence *et al.*, 2005),

roads/transportation systems (Blake et al., 2017; Guffanti et al., 2009), electrical infrastructure 75 (Bebbington et al., 2008; Wilson et al., 2014), farmland/livestock (Annen & Wagner, 2003) or 76 water reservoirs and vegetation (Wilson et al., 2012). In response to such threats, numerous 77 78 researches have been carried out for providing authorities, stakeholders and population with tools for both volcanic crises management and long-term urban planning. Particularly, in this latter 79 case, tephra fallout hazard maps have been produced using different strategies that rely on field 80 data of past eruptions (e.g., Orsi et al., 2004) or which combine field data and numerical 81 82 modelling (Barberi et al., 1990; Bursik, 2001; Cioni et al., 2003; Macedonio et al., 1988). This latter approach is normally coupled with semi-probabilistic to fully probabilistic Monte Carlo 83 84 techniques (Hurst & Smith, 2004) to sample model input parameters, and takes advantage of the great availability of tephra transport and deposition numerical models. As examples, tephra 85 fallout hazard maps have been produced using different models such as HAZMAP (Bonasia et 86 al., 2011; Capra et al., 2008; Costa et al., 2009; Macedonio et al., 2005), TEPHRA2 (Biass & 87 Bonadonna, 2013; Biass et al., 2014; Bonadonna et al., 2005; Tsuji et al., 2017; Yang et al., 88 2021), FALL3D (Costa et al., 2006; Folch et al., 2009; Folch et al., 2020; Prata et al., 2021; 89 Scaini et al., 2012; Vázquez et al., 2019), VOL-CALPUFF (Barsotti et al., 2018; Barsotti & 90 Neri, 2008; Barsotti et al., 2008) and ASH3D (Alpízar Segura et al., 2019; IG-EPN et al., 2019; 91 Schwaiger et al., 2012; Yang et al., 2020) models. The key elements for the modelling of tephra 92 dispersal and for the development of probabilistic maps are: i) the identification of the eruptive 93 scenarios that describe the eruptive history of the volcano; ii) the quantification of the 94 uncertainty range of the eruptive source parameters (ESPs) related to each scenario; and iii) the 95 estimation of the temporal recurrence rate and/or the probability of occurrence of the identified 96 97 scenarios within defined temporal frames (Sandri et al., 2016). Especially for the last two elements, uncertainty was quantified in recent hazard-related studies mostly through comparison 98 between available field data and existing global volcanological databases (see for example Biass 99 & Bonadonna, 2013). How the input uncertainty propagates through the model, and how it is 100 influenced by wind field variability has been the topic of several studies (Bursik et al., 2012; 101 Macedonio et al., 2016; Madankan et al., 2014; Pouget et al., 2016; Scollo et al., 2008; 102 Stefanescu et al., 2014). An important source of uncertainty that has a direct impact on final map 103 production has been however poorly considered so far, that is, the uncertainty related to the 104 inadequacy of the numerical model itself, which is linked to the necessary physical 105 approximations (including neglected physical processes) that allow acceptable computational 106 times. Constraining the model-related uncertainty is an open challenge in common with other 107 geophysical mass flow modeling efforts, and requires a statistically-based and multi-model 108 approach (Bevilacqua et al., 2019; Costa et al., 2016b; Patra et al., 2020; Patra et al., 2018). 109

This paper presents a tephra fallout hazard assessment study, which focuses on the area 110 of Quito, Ecuador's capital city. In order to perform this study, we focus on Cotopaxi and 111 Guagua Pichincha, which are located nearby the city and are currently active volcanoes with 112 recent eruptions. To develop probabilistic hazard maps, we employ a model that is the result of a 113 coupling between the plume model PLUME-MoM (de'Michieli Vitturi et al., 2015) and the 114 tephra dispersal model HYSPLIT (Stein et al., 2015), as already performed by Tadini et al. 115 (2020) and Pardini et al. (2020). There have not been so far any attempts to use this coupled 116 model to produce probabilistic hazard maps for tephra fallout, although HYSPLIT is currently 117 used by several Volcanic Ash Advisory Centers (Mastin et al., 2017) for operational purposes: 118 119 this study is therefore a first step to a broader usage of this model outside the domain of real-time tracking of volcanic particles. The main novelty of this study is the implementation of a 120

procedure that takes into account three major sources of uncertainty during the production of tephra fallout hazard maps (on the ESPs, the model, and the eruption type occurrence probability). Particularly, the definition of these uncertainties has been the topic of two precedent studies (Tadini *et al.*, 2020, 2021)developed in the framework of the same research project (see Acknowledgements).

We firstly introduce Cotopaxi and Guagua Pichincha volcanoes (section 2). Then we describe the modelling strategy (section 3.1), the uncertainty quantification for ESPs and eruption type occurrence (section 3.2), and the procedure for hazard maps and hazard curves production. Finally, section 4 focuses on the presentation of the maps/curves and on the discussion of their main implications, including the areas and the people potentially involved by each hazard isoline.

132 2 Background

133 Quito, Ecuador's capital city, is located in the inter-andean valley, within the province of

Pichincha (Fig. 1a). With almost three millions of inhabitants it is also the largest city in the
country, it hosts the largest airport in Ecuador and it is in the middle of the most important road
systems (e.g. the "Pan-American highway"; Fig. 1a).



Figure 1. a) Location of Cotopaxi and Guagua Pichincha volcanoes with respect to the capital 138 city Quito and the main towns and infrastructures in the region. Light blue and light green 139 dashed boxes represent, respectively, the extents of Figs. 6-7 and 9-10; sensitive sites within the 140 141 capital city of Quito considered in this study are shown. Coordinates are in the UTM WGS84 17S system. Service Layer Credits, source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, 142 CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community; b) Cotopaxi 143 volcano seen from North; c) Guagua Pichincha volcanic complex and the city of Quito seen from 144 145 East.

146 2.1 Cotopaxi

According to Hall & Mothes (2008), the eruptive history of Cotopaxi volcano (Fig. 1a 147 and b) began about 500 ka and has been firstly characterized by dome-forming to Plinian 148 eruptions (up to VEI 4-5 or greater), which erupted mostly rhyolitic magmas (70–75 wt.% SiO₂). 149 In contrast, from ~4 ka until present day, magmas erupted were almost all andesitic in 150 composition (56-62 wt.% SiO₂). The latter period of activity (i.e. the last 2000 years) with 151 andesitic magmas include violent Strombolian VEI 2-3 (in the XIX century, Pistolesi et al., 152 2011), sub-Plinian VEI 3-4 (AD 1877 or XVIII century, Pistolesi et al., 2011) and Plinian VEI 4-153 5 (Layer 3/X, 820±80 years BP; Layer 9/5/L-2, 1,180±80 years BP; Barberi et al., 1995; Biass & 154 Bonadonna, 2011; Hall & Mothes, 2008) eruptions. The last eruption of Cotopaxi is the AD 2015 155 VEI 1-2 eruption, characterized by an opening hydrovolcanic phase followed by a ~3 months 156 long ash emission, which erupted a total of ~ 8.6×10^5 m³ of tephra and caused a severe air traffic 157 disturbances and impacted rural activities in the region (Bernard et al., 2016; Gaunt et al., 2016; 158 159 Hidalgo et al., 2018).

160 Cotopaxi volcano has been the subject of tephra fallout hazard assessment studies (Biass & Bonadonna, 2013; Hall et al., 2004a; Hall et al., 2004b; Hall & von Hillebrandt, 1988a; Miller 161 et al., 1978) and risk (Biass et al., 2013). Particularly, Biass & Bonadonna (2013) performed a 162 probabilistic tephra fallout hazard assessment for five eruption types (two with fixed ESPs and 163 164 three with ESPs defined as a variation range), with magnitudes ranging from VEI 3 to 5. For each eruption type, 1,000 runs were carried out by using the TEPHRA2 model. As input 165 parameters for this model, Biass & Bonadonna (2013) considered, for each run, i) a wind profile 166 sampled from the NOAA NCEP/NCAR Reanalysis 1 database (Kalnay et al., 1996) and ii) 167 168 erupted volume, plume height and median grainsize sampled from a specific distribution. The probability of tephra accumulation in a given time window was presented by the authors through 169 170 three different outputs, i) probability maps for a given tephra accumulation, ii) isomass maps for a given probability value and iii) hazard curves of tephra load for several locations, including 171 Quito city center and the town of Latacunga. The authors calculated also the probability of 172 occurrence of an eruption of VEI \geq 3 for the next 10 (~36%) and 100 (~99%) years. Biass *et al.* 173 (2013) performed instead a risk assessment for eruptions with VEI \geq 4, and highlighted the 174 possibility of roof collapse due to tephra loading of several thousands of houses in the proximity 175 176 of the volcano, the destruction of agriculture and the possible disruption of major roads. Later, Volentik & Houghton (2015) performed a more extended hazard assessment focused on the 177 potential impact of tephra fallout on Quito International airport from explosive eruptions of 178 different Ecuadorian volcanoes. They used the TEPHRA2 model and NCEP/NCAR Reanalysis 1 179 wind data, while plume height, eruption duration, total mass and median/sorting of grain size 180 were sampled from uniform, log-uniform or log-normal distributions. Specifically for Cotopaxi, 181 the study indicated, at Quito airport, a yearly probability of mass accumulation of 1 mm and 10 182 mm of, respectively, ~14% and 2.5%. Recently, a multi-hazard map for Cotopaxi was released 183

divided in three sectors, North (Mothes et al., 2016a), South (Mothes et al., 2016b) and East 184 (Vasconez et al., 2017). In the first two maps, tephra fallout hazard assessment was treated as the 185 expected tephra accumulation (with thresholds of 5 and 25 cm) in case of an eruption with VEI 186 187 3-5, based on field data of past eruptions with similar magnitudes. In the map of Vasconez et al. (2017), instead, the authors presented the most likely (80%) distribution for a VEI 3 eruption 188 (similar to the AD 1877) based on 120 simulations (1 per month for 10 years, windfield 189 reanalysis 2007-2017) using the ASH3D model (Schwaiger et al., 2012). In this map, Quito is 190 191 potentially (<20% probability) affected by ashfall deposits of thickness between 10 and 100 mm. Finally, additional tephra fallout maps have been presented in the work of Cruz Roja Ecuatoriana 192 (2020), which includes maps for 5 eruptive scenarios (120 simulations each using the ASH3D 193 model) for different probability thresholds (1, 25, 50, 75 and 99%) 194

195 2.2 Guagua Pichincha

The Pichincha volcanic complex (Fig. 1a and c) is composed of three distinct edifices, the 196 youngest of which is Guagua Pichincha (4,784 m a.s.l.). During the eruptive history of this latter 197 (starting from 60 ka), all the erupted products were of andesitic to dacitic composition (59-66 198 wt.% SiO₂; Robin et al., 2010). Guagua Pichincha volcano has been affected by two major sector 199 collapses (at ~11 ka and ~4 ka): after the latter one ("Toaza" sector collapse; Robin et al., 2008) 200 the eruptive history has been characterized mainly by phases of growth and destruction of a 201 dome complex located in the landslide scar ("Cristal Dome"). From ~4 ka up to AD 1660, Robin 202 et al. (2008) recognized three major eruptive cycles that occurred during the 1st and 10th century, 203 and in AD 1660 (named respectively "I century", "X century" and "Historic"), each of them 204 separated from the others by repose times of the order of hundreds of years. Each cycle was 205 initiated with effusive, dome-forming eruptions alternated with low-magnitude vulcanian 206 episodes, and was closed by a final, medium-large magnitude (VEI 3-4) sub-Plinian to Plinian 207 208 eruption (Robin et al., 2008). The eruption that ended the Historic cycle occurred in AD 1660 (Robin et al., 2008) and caused severe tephra fallout in Quito and pyroclastic density currents on 209 the western side of the volcano (Wolf, 1904). After more than 300 years of quiescence, volcanic 210 211 activity at Guagua Pichincha started over in AD 1999, lasting for almost two years until AD 2001. This period, which included several Vulcanian events and a series of dome-forming 212 eruptions (Garcia-Aristizabal et al., 2007; Wright et al., 2007), might represent the beginning of 213 a new eruptive cycle like those cited in Robin et al. (2008). 214

The first tephra fallout hazard assessments at Guagua Pichincha have been done by Hall 215 & von Hillebrandt (1988b) and Barberi et al. (1992). Particularly, the latter authors considered 216 the Plinian eruptions of the X century and Historic cycles as the events with the maximum size 217 among those potentially expected in the future, and they calculated the expected tephra 218 219 accumulation using the model of Armienti et al. (1988). For this model they considered two single meteorological profiles (i.e. wind) and specific eruptive source parameters for each of the 220 two eruptions. Resulting maps described tephra accumulation in term of thickness (from 5 to 50 221 222 cm) and a zonation of the area surrounding Guagua Pichincha in different classes according to the impact of tephra fall and other volcanic-related hazards. Volentik & Houghton (2015), in the 223 case of an eruption from Guagua Pichincha volcano, indicated at Quito airport a probability of 224 accumulation of 1 mm and 10 mm of ash of 17.5 and 7 %, respectively. Finally, a multi-hazard 225 map for Guagua Pichincha was published (IG-EPN et al., 2019) within the already cited work of 226 Cruz Roja Ecuatoriana (2020). For this map, the ASH3D model has been used (Schwaiger *et al.*, 227 228 2012), and tephra fallout hazard assessment has been treated in a semi-probabilistic way. Three scenarios linked to three past eruptions (AD 1999-2001, AD 1660-Historic, X century) have 229

been considered with fixed eruptive source parameters, while wind profiles were statistically

sampled at each iteration. Resulting maps described the expected tephra thickness (in mm) for
 given probabilities (1, 25, 50, 75 and 99%).

- 233 **3 Methods**
- 2343.1 Numerical modelling
- 235 3.1.1 PLUME-MoM/HYSPLIT model
- 236

After its first release (de'Michieli Vitturi et al., 2015), PLUME-MoM has been recently 237 upgraded to a new version (PLUME-MoM-TSM, with "TSM" standing for "two-sized 238 moments"; de' Michieli Vitturi & Pardini, 2021). This model describes the steady-state dynamics 239 of a plume in 3D coordinates through a system of equations for the conservation of mass, 240 momentum, energy, and the variation of heat capacity and mixture gas constant. The model 241 considers radial and crosswind air entrainment, and it adopts the method of moments to describe 242 a continuous size distribution of one or more group of particles (e.g., with different densities, 243 shapefactors,etc.). Moreover, PLUME-MoM-TSM can simulate, for sustained eruptions, the 244 initial spreading of the umbrella cloud due to the development of gravity currents originating 245 from the plume overshoot (i.e. above the neutral buoyancy level). This feature allows a more 246 detailed computation of the spreading of the umbrella cloud, especially in its upwind part. In 247 PLUME-MoM-TSM, the amount of mass released is computed i) along the plume centerline, at 248 emission points located at fixed height; ii) from the area defined by the umbrella cloud. Both the 249 emission points and the umbrella cloud area represent the source locations for HYSPLIT. 250

HYSPLIT (Stein *et al.*, 2015) is an atmospheric dispersion model that describes the 251 advection/diffusion of air parcels considering a Lagrangian approach and that computes the 252 concentrantion/sedimentation of pollutants (volcanic particles in our case) at fixed receptors 253 (Eulerian approach). The dispersion of a pollutant is described by assuming three types of 254 configuration, "3D particles", "puff" or hybrid configurations between the two. Particularly, 255 while a 3D particle is a point mass transported by the wind that does not grow or split, a "puff" 256 represents the distribution of a large number of 3D particles with a predefined concentration 257 distribution in both the horizontal and vertical directions. The puffs expand with atmospheric 258 259 turbulence, and if they exceed the size of the meteorological grid cell they are split into several new puffs, each with their respective pollutant mass. We have used the hybrid configuration, 260 which considers 2D objects with zero vertical depth and planar mass. In this way, such objects 261 move horizontally according to the "puff" configuration, while in the vertical direction they 262 move like 3D particles (i.e. they do not expand nor split) mostly depending on the terminal fall 263 velocity of the pollutant. As discussed in Tadini et al. (2020) this configuration allows use of a 264 limited number of puffs (thus reducing computationl times) to properly capture both the 265 horizontal dispersion and the vertical wind shears. In this work we have used the April 2018 266 release version of HYSPLIT, with the modifications detailed in Tadini et al. (2020). 267

268

3.1.2 Uncertainty quantification for the numerical model

In this paper we apply the procedure for the quantification of the uncertainty of tephra fallout model described in Tadini *et al.* (2020). In the latter, the coupled PLUME-MoM/HYSPLIT model has been used to reproduce four past eruptions from Tungurahua and Cotopaxi volcanoes (in Ecuador) and Puyehue-Cordón Caulle volcano (in Chile). Input parameters for these eruptions have been collected after a thorough literature review, as well as from ground deposit and plume height measurements. The uncertainty was quantified by computing the differences between modeled and observed data of plume height above the vent, and mass loading and grain size at given stratigraphic sections. Regarding mass loading (kg/m²) in particular, for each eruption type and meteorological dataset tested, Tadini *et al.* (2020) calculated the model mean overestimation (MO) and the mean underestimation (MU),

279
$$\begin{cases} MO = \frac{\sum_{i=1}^{N_o} \Delta_i}{N_o} \text{ for } \Delta_i > 0\\ MU = \frac{\sum_{i=1}^{N_u} \Delta_i}{N} \text{ for } \Delta_i < 0 \end{cases}$$
(1)

where Δ is the difference between the computed and the observed values of mass loading 280 (in kg/m²) evaluated for sections with indexes from i=1 to, respectively, N_0 and N_0 . These latter 281 are the numbers of sections with overestimation and underestimation, respectively. MO and MU 282 values were divided by the mean value of mass loading measured in the field for all the 283 considered sections (MML), thus giving two coefficients (MO/MML and MU/MML), which we 284 will use in section 3.3.1 to account for, respectively, model overestimation and underestimation. 285 This approach has the advantage of summarizing the errors in two coefficients. However, we 286 note the average of differences at all the sections may be far from representative of the errors at 287 288 the sites with greatest or lowest accumulations. Results of the study of Tadini et al. (2020) highlight that: i) the model tends to have (for larger magnitude eruptions) a higher degree of 289 overestimation rather than understimation (i.e. MO/MML > MU/MML); ii) sections with 290 underestimation tend to be both in more proximal and medial/distal locations from the vent, 291 while sections with overestimation tend to be more concentrated in proximal/medial locations 292 mostly along the main dispersal axis of the deposit; iii) among the different tested meteorological 293 datasets, none of them is systematically better than the others in minimzing the differences 294 between modeled and observed mass loading values. With respect to this latter point, the authors 295 showed also that the employment of more spatially and temporally refined meteorological 296 datasets do not always improve the result. 297

Given the new features introduced in PLUME-MoM (see Section 3.1.1), we ran the 298 simulations again for the two eruptions with the largest size (in terms of magnitude) used by 299 Tadini et al. (2020), which are Tungurahua 2006 (sub-Plinian, VEI 3-4; Eychenne et al., 2012) 300 301 and Puyehue-Cordón Caulle 2011 (sub-Plinian, VEI 4; Bonadonna et al., 2015a). For these eruptions we have used the same input parameters as those used by Tadini et al. (2020) along 302 with the GDAS meteorological dataset (to be consistent with the one used in this work, see 303 section 3.2.2). In order to take into account the full uncertainty of the model, we chose the two 304 MO/MML and MU/MML largest values, , which were 305

- 306
- 307 MO/MML = 1.48
- 308 MU/MML = -0.49
- 309 These two values are related to the Puyehue-Cordón Caulle 2011 sub-Plinian eruption simulated
- using the GDAS meteorological data. As a comparison, the two values from Tadini *et al.* (2020)
- are larger (MO/MML = 3.15; MU/MML = -1.03), highlighting how the features introduced with
- the new version of PLUME-MoM have allowed reduction of the uncertainty of the model.

313

3.2 Eruption type probabilities and input parameters for the numerical model

314 3.2.1 Eruption type probabilities

To provide a quantification of the uncertainty in future eruption occurrences at both 315 Cotopaxi and Guagua Pichincha volcanoes, Tadini et al. (2021) performed an expert elicitation 316 session aimed at quantifying such values, which we will use in the merging of maps/curves (see 317 section 3.3.3). In general, during an elicitation session (Aspinall, 2006; Aspinall et al., 2019; 318 Bevilacqua et al., 2015; Neri et al., 2008; Tadini et al., 2017a) selected experts are asked to 319 provide their judgements (in the form of three percentiles, normally the 5th, 50th and 95th) on two 320 different questionnaires. Firstly, they are asked factual questions with known answers to the 321 organizers, to which they answer by providing credible intervals that capture the 'true' values 322 (seed questions). The score that each expert got assigned after filling this first questionnaire is 323 then used to pool all experts' judgements on a second questionnaire. This questionnaire enlists a 324 325 number of "target" questions with unknown answers, which specifically address the problem(s) under investigation, in order to obtain group synthesized answers called 'decision-maker'. 326

In Tadini et al. (2021), a total of 20 experts (with different background, experience and 327 328 knowledge on the studied volcanoes) were calibrated through 14 seed questions on south American (particularly Ecuadorian) volcanism and numerical modelling of tephra transport and 329 dispersal. Thus the experts were weighted using two performance-based schemes: the CM 330 (Classical Model, Cooke, 1991) and ERF (Expected Relative Frequency, Flandoli et al., 2011) 331 methods, and compared to an equal weight combination. The experts were then asked to provide 332 333 their answers on 55 target questions on both future eruption occurrences and eruptive source parameter uncertainty ranges (see section 3.2.2). Regarding future eruption occurrences, two 334 time frames were distinguished: the next eruption and the next 100 years. The former was aimed 335 at assessing what would be the probability for the next eruption of a specific type (the mean 336 elicited values summed up to 100%), while the 100 years focused on the probability of having at 337 least one eruption of a specific type within the next 100 years (no constraints on the elicited 338 values sum). This was made in order to consider the case of new large scale eruptions in the next 339 100 years, albeit preceded by smaller size events. The comparison to previous estimates based on 340 temporal models of the eruptive record is thoroughly discussed in Tadini et al. (2021). A major 341 advance was related to having obtained a probability distribution of eruption occurrence over an 342 uncertainty range, thus enabling a doubly stochastic approach (Bevilacqua et al., 2020; 343 Bevilacqua et al., 2018; Bevilacqua et al., 2016; Marzocchi et al., 2008; 2010; Neri et al., 2008; 344 Tadini et al., 2017b). The concept of "probability of probability" is the key to assess the 345 epistemic uncertainty affecting the probability of occurrence of eruption types, thus having 346 347 implications on the entire subsequent hazard assessment. This concept is opposed to the aleatoric uncertainty expressed by these probabilities. More details on this topic may be found in the 348 above-mentioned studies. 349

In this paper we use the results related to the CM model, and the corresponding probability distributions for the eruption types considered in this study (i.e. sub-Plinian and Plinian) are reported in Fig. 2.



353

Figure 2. Uncertainty distributions according to the Classical Model method for the probability of occurrences of the sub-Plinian and Plinian eruption types for a) Cotopaxi and b) Guagua Pichincha volcanoes. For both volcanoes the uncertainty distributions are shown fori) the probability that next eruption will be either sub-Plinian or Plinian (left panels) and ii) the probability that there will be at least one eruption of each size within the next 100 years (right panels). y-axis describes the density of the probability density function. Data from Tadini *et al.* (2021).

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Mean values of the probability distributions are reported in Table 1, while the three percentiles for each eruption type are reported in Table S1 from the supporting information. For Cotopaxi, the graphs of Fig. 2 and the mean probabilities of Table 1 indicate that eruptions involving rhyolic magmas are less probable than their andesitic counterparts for the next eruption but also in the next 100 years time frames. However, the mean probability that the next eruption will involve a rhyolitic magma is not negligible (10.5% - Table 1). We note that sub-Plinian and Plinian eruptions give a summed mean probability of occurrence for the four eruption types of ³⁶⁹ ~29%, while for Guagua Pichincha the sum of the mean probabilities for sub-Plinian and Plinian

370 is 36% (see Table 1).

371

Eruption Cotopaxi	Next eruption (%)	Next 100 years (%)		
sub-Plinian Rhyolitic	5.9	12		
Plinian Rhyolitic	4.6	12		
sub-Plinian Andesitic	12	31		
Plinian Andesitic	6.9	17		
Eruption Guagua Pichincha	Next eruption (%)	Next 100 years (%)		
sub-Plinian	22	28		
Plinian	14	21		

Table 1. Mean values of the distributions of Figure 2. Data from Tadini *et al.* (2021).

373 3.2.2 Input parameters for the numerical model

We used uncertainty distributions to sample three important parameters for tephra fallout hazard assessment and numerical modeling, which are eruption duration, total mass of the fallout deposit, and average plume height. Such distributions were defined by the expert elicitation session thoroughly described in Tadini *et al.* (2021) and summarized in section 3.2.1. We report these uncertainty distributions in Fig. 3 and the mean values of such distributions in Table 2, while the three elicited percentiles (5th, 50th, and 95th) are reported in Tables S1 and S2 from the supporting information.

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EruptionDurationCotopaxi[hours]		Total massAverage plumefallout [109 kg]height [km]		MdΦ	σΦ
sub-Plinian Rhyolitic	3.3 (4.1)	49 (36)	14 (18)	-0.5 - 4	2.1 - 3.1
Plinian Rhyolitic	6.2 (7.6)	270 (365)	22 (27)	-0.4 - 4	2 - 3.3
sub-Plinian Andesitic	1.8 (3.8)	27 (31)	16 (17)	-1.2 - 4.5	1.7 - 3.4
Plinian Andesitic	2.2 (7.7)	240 (262)	24 (24)	-0.8 - 4.4	1.8 - 3.3
Eruption Guagua Pichincha	Duration [hours]	Total mass fallout [10 ⁹ kg]	Average plume height [km]	MdΦ	σΦ
sub-Plinian	2.2 (3.8)	24 (25)	16 (16)	1.3 - 3.8	2.2 -3.3
Plinian	4 (7)	130 (150)	24 (21)	1.5 - 3.7	2.1 - 3.2

Table 2. Mean values for duration, total fallout mass and average plume height (Figure 3 and

Tadini *et al.*, 2021) and maximum-minimum values for median (Md Φ) and sorting ($\sigma\Phi$) of the total grain-size distributions (Costa *et al.*, 2016a). Values in parenthesis are mean values after the application of the relation of Mastin *et al.* (2009) described in section 3.3.1.





Figure 3. Eruptive source parameters (total eruption duration, total fallout mass and average plume height), uncertainty distributions according to the Classical Model method (from Tadini *et al.*, 2021; upper panels) and uncertainty distributions recalculated after the application of the relation of Mastin *et al.* (2009) (eqs. 2 and 3 - lower panels) for a) Cotopaxi and b) Guagua Pichincha volcanoes. y-axis describes the density of the probability density function.

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394 For other parameters, such as total grain-size distribution (TGSD), particle densities, particle shape factors (i.e. sphericity), and initial volatile content of magma, we considered an 395 uncertainty range variable between two end members. In detail, for particle density we 396 considered that this parameter increases linearly between those typical of a coarser and a finer 397 grain size end-members, according to Bonadonna & Phillips (2003). Uncertainty bounds for this 398 latter parameter have been derived from Bonadonna & Phillips (2003) and Pistolesi et al. (2011). 399 For TGSD, instead, we considered the relationship discussed in Costa et al. (2016a), who 400 proposed that TGSD distributions (for each eruption and magma types) can be described by the 401 sum of two log-normal distributions as a function of plume height and magma viscosity. Details 402 of these relations are provided in the Appendix. In our study, we have considered TGSD in the 403 range $\Phi = -6$ to $\Phi = 10$ (see Table 2 for the range of median and sorting of the total grain size 404 distributions used in the simulations). Regarding the uncertainty ranges of the other parameters, 405 we relied on the constraints given in literature for the pre-eruptive water contents for Cotopaxi 406 and Tungurahua magmas (Andújar et al., 2017; Martel et al., 2018; Samaniego et al., 2010; 407 Wright et al., 2007), and particle shape factors (Riley et al., 2003) of other volcanoes. The 408 409 complete list of the parameters (other than those reported in Table 2) is available in Table S3 from the supporting information. 410

For meteorological data, we have used those deriving from the GDAS forecast data 411 (NOAA, 2004), covering the period December 2004 – December 2019. This meteorological 412 dataset (tested by Tadini et al., 2020) collects atmospheric data on 23 pressure levels (plus 413 ground data) with a spatial grid resolution of 1° x 1° and a temporal resolution of 3 hours. An 414 example of wind directions/velocities at a selected pressure level (200 hPa) above Cotopaxi 415 volcano is provided in Figure S1 from the supporting information, which shows that main wind 416 directions are toward NW/W/SW with the exceptions of December and January. Despite the 417 availability of more spatially and temporally refined meteorological datasets (e.g. the ERA5 418 reanlysis dataset; Hersbach et al., 2020), we have chosen the GDAS meteorological dataset for 419 two reasons. Firstly, GDAS data can be directly read by HYSPLIT after their download without 420 conversion and/or assemblages from separate files (as it is necessary for the ECMWF datasets 421 like ERA-Interim or ERA5). This has the advantage of simplifying the procedure but also 422 avoiding possible errors during the conversion procedure. Secondly, Tadini et al. (2020) showed 423 that there is not a meteorological dataset that systematically provides better results (see Section 424 3.1.2), and the uncertainty of the model could be only partially be ascribed to the employment of 425 one meteorological dataset compared to another. Future developments could include a deeper 426 usage of the newly released datasets like the ERA5 in order to provide a comparison with the 427 present results. 428

429 3.3 Hazard maps and curves

430 3.3.1 Parameters sampling and maps production

In order to explicitly quantify the different uncertainties, in this study we have
implemented a new and comprehensive procedure for parameter sampling and map production,
as illustrated in Fig. 4. This figure shows the procedure for each eruption type and for each
iteration.



Figure 4. Sketch of the procedure for map production. a) Parameter sampling for each iteration. 436 Mass, duration and plume height are sampled from the elicited distributions and adjusted 437 according to Mastin et al. (2009), while other parameters are sampled from uniform distributions 438 439 and TGSD is sampled using the relation of Costa et al. (2016a); b) processing of simulations. A total of 3000 simulations for each eruption type (250 per month) are done. Each simulation 440 output is corrected with the two coefficients that account for model uncertainty (MO/MML and 441 MU/MML) and two additional maps are created. Mass loading values (ML) are then converted 442 to thickness (Thk) using a mean value of deposit density (ρ_d); c) post processing and 443 development of probability maps. For each map and each thickness threshold (1, 3, 10, 30, 100, 444 300 mm) it is evaluated the probability that, at each node of the map, Thk \geq threshold. Three 445 final maps are produced, "Natural", "Lower" and "Upper". 446

447

The uncertainty affecting the eruptive source parameters (ESPs) was taken into account with a Monte Carlo sampling (Fig. 4a). The three main ESPs (eruption duration, total mass of tephra fallout deposit, and average plume height) have been sampled directly from the distributions provided by Tadini *et al.* (2021) and reported in Fig. 3.

However, in order to avoid the use, within each simulation, of physically unrealistic combinations of parameters, we have considered the relations described in Mastin *et al.* (2009) that link plume height (in km) with volumetric flow rate (VFR in m^3/s) and total volume (V in km³) of the fallout deposit, which are

456

457 $H = 2.00 * VFR^{0.241}$

458 $H = 25.9 + 6.64 \log_{10}(V)$

(2) (3)

Therefore, we have defined three possible cases, imposing that one third of the Monte Carlo iterations follows each case:

• total mass is sampled and duration/plume height are calculated (equations 2-3);

• plume height is sampled and total mass/duration are calculated (equations 2-3);

• duration and total mass are sampled and plume height is calculated (equation 2).

For the latter case, duration and total mass have been sampled independently due to the 464 absence of a strong relationship between eruption duration and the other parameters (as also 465 pointed out by Mastin et al., 2009). In detail, the total mass of tephra fallout deposit (in kg) 466 enabled the calculation of the mass flow rate (kg/s) using eruption duration. To convert our mass 467 and mass flow rate to, respectively, volume and volumetric flow rate, we have used magma DRE 468 densities and tabulated values from Spera (2000) of 2340, 2220 and 2110 kg/m³ for, respectively, 469 andesitic, dacitic and rhyolitic melts. Density values have been chosen corresponding to magma 470 water contents compatible to the ranges used here (see Table S2 from the supporting 471 472 information). This procedure has the advantage of creating set of parameters physically related for each simulation, although it introduces some alterations with respect to the original elicited 473 values. We found these differences not significant, except for eruption duration (see Fig. 3), 474 which reduced the probability of samples below 60 minutes, and thus had mean values slightly 475 higher than the elicited one for all the eruption types. Conversely, when analyzing the 476 contribution of the three above-mentioned cases in exploring the sample space, we noted that 477 only method 3 (i.e. duration/total mass sampled and plume height calculated) captures the 478 longest elicited durations (see Fig. S2 from the Supporting Information). Nevertheless, although 479 this is significant to mention in terms of seeking future improvements of input parameters 480 handling, the changes in duration do not significantly influence our hazard assessment because 481

they mostly affect the eruptions of the shortest duration and, in absolute terms, prolong them of a 482 few tens of minutes. In general, since our study focuses on medium-large magnitude eruptions 483 (i.e. VEI 3-4, sub-Plinian to Plinian), using the relations of Mastin et al. (2009) is appropriate in 484 order to avoid the limitations of these relations themselves, which are less precise for small-size 485 eruptions. 486

We highlight that PLUME-MoM cannot take at the same time mass flow rate and plume 487 height as input parameters, and thus the plume height in our procedure (both sampled from the 488 elicited distribution of Tadini et al., 2021 or calculated after Mastin et al., 2009) can be different 489 with respect to the plume height calculated by PLUME-MoM by using the sampled total mass 490 and duration. In case the elicited plume height is sampled (and therefore mass flow rate is 491 calculated with Mastin et al., 2009 and provided as input to PLUME-MoM), we found that 492 PLUME-MoM can provide plume height values ~30-40% lower, at the end of simulation, with 493 respect to those used to calculate the total mass/duration. This is perhaps related to the fact that 494 the relation between plume height and mass flow rate of Mastin et al. (2009) is mostly based on 495 maximum plume height values while the elicited plume heights arevalues averaged over the 496 course of the eruption. However, the uncertainty bounds provided by Mastin et al. (2009) and the 497 498 uncertainty range of our elicitation are fully overlapping and greater than the above-mentioned differences. 499

As previously mentioned, plume height and magma viscosity enabled us to calculate total 500 grain-size distribution according to the relation proposed by Costa et al. (2016a) (see previous 501 section, Appendix, and Table 2). However, differences in the TGSD due to the plume height 502 discrepancy are not significant. 503

We finally remark that the duration of the eruption was also used to select (from the 504 GDAS meteorological file covering the period 2004-2019) a time period for meteorological data. 505 To this time period, additional 6 hours of simulation (with no emission) have been added to 506 allow the particles to settle. To account for monthly variations in atmospheric data (see Figure S1 507 from the supporting information), we have performed the same number of simulations for each 508 month (250, chosen as the best compromise between output accuracy and computation time). In 509 total, we performed 3000 simulations for each eruption type. 510

The uncertainty due to the numerical model has been quantified during the processing of 511 simulations (Fig. 4b). During this stage, the sampled parameters have been assembled to create 512 an input file for the model, and at the end of the simulation an output in the form of a sampling 513 grid has been provided, where each node $N_{x,y}^N$ (with x and y being latitude and longitude 514 coordinates) has a mass loading value ML (in kg/m²). By using the two coefficients MO/MML 515 and MU/MML described in Tadini et al. (2020) and in section 3.1.2, two additional maps were 516 created: 517

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- 519

519	• a map with nodes $N_{x,y}^L$ that	corrects	model o	overestimation,	such	that $ML(N_{x,y}^L)$) =
520	$ML(N_{x,y}^N)/(1 + MO/MML),$	where	MO/MN	ML = 1.48 is	the	coefficient	of
521	overestimation (see section 3.1.	2);					

• a map with nodes $N_{i,j}^U$ that corrects model underestimation, such that $ML(N_{x,y}^U) =$ 522 $ML(N_{x,y}^N)/(1 + MU/MML)$ where MU/MML = -0.49 is the coefficient of 523 underestimation (see section 3.1.2). 524

The mass loading values of each map (in kg/m^2) were then converted into thickness 525 values (in mm) by dividing them with deposit density average values. For Cotopaxi we have 526 used 825 kg/m³ for andesitic (average among values used by Tsunematsu & Bonadonna, 2015) 527 and 560 kg/m³ for rhyolitic (Bonadonna et al., 2015b) magmas. For Guagua Pichincha, given the 528 general paucity of published data, we have collected 22 samples from tephra fallout deposits 529 from both the X century (12 samples) and Historic (10 samples) eruption cycles (Figure S3 from 530 the Supporting Information). The average value of the calculated deposit densities (measured as 531 the ratio mass/volume of the 22 samples) yields an average value of 745 kg/m³. 532

Once all simulations were finished, probabilistic maps were produced in a postprocessing stage (Fig. 4c) following the approach of Bonadonna (2006). According to this latter, the probability P_{τ} at each node $N_{x,y}^N$ (for the simulation output, same for $N_{x,y}^L$ and $N_{x,y}^U$) is determined by summing the number of times a certain thickness threshold (Thk) is reached and dividing it by the total number m of the simulations:

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$$P_{\tau}(N_{x,y}^{N}) = \frac{\sum_{i=1}^{m} n_{i}}{m}$$
540 where
541
$$n_{i} = \begin{cases} 1, & if \left[Thk(N_{x,y}^{N}) \ge \tau\right] \\ 0, & otherwise \end{cases}$$
(5)

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In this study we have used six different thresholds τ (in mm, Fig. 4c), chosen to be comparable with existing hazard maps and hazard-related studies. Three maps were in the end produced ("Lower", "Natural" and "Upper"), defining a set of maps that quantify the uncertainty associated with the model. This procedure has been applied for all the six eruption types considered in this study (see section 3.3.2).

548 3.3.2 Maps and curves format

We focused on medium to large magnitude eruptions, i.e. those with VEIs ≥ 3 549 corresponding to sub-Plinian to Plinian eruptive styles (i.e. those for which the model performs 550 better). For the two studied volcanoes, this corresponds to four eruption types for Cotopaxi (sub-551 Plinian/Plinian with rhyolitic magmas, and sub-Plinian/Plinian with andesitic magmas) and two 552 eruption types for Guagua Pichincha (sub-Plinian and Plinian with dacitic magmas). Different 553 maps have therefore been produced for each eruption type and thickness threshold (see section 554 3.3.1). Moreover, for each volcano, the corresponding maps have been merged to produce a 555 unique set of maps according to the procedure detailed in section 3.3.3. To limit the 556 557 computational times, the computational domain of the simulations has been imposed equal to a square of 1.5°x1.5° centered on each volcano. 558

The resulting maps (produced through a post-processing procedure into the ArcGIS10© 559 software) follow a format similar to those proposed by Biass & Bonadonna (2013), which are: i) 560 probability maps (in which we are showing the 10% and 50% probability isolines) corresponding 561 to a thickness threshold; and ii) isopach maps corresponding to a specific probability (10% and 562 50%). In addition, we derived hazard curves, which describe the probability of exceeding certain 563 values of tephra accumulation at a given location (Bonadonna, 2006), at 10 sensitive sites within 564 the city of Quito. These sites have been chosen because they could be heavily affected by tephra 565 fall and could cause major issues to population and authorities. These sites are (Fig. 1a): Quito 566 airport, Quito city center (UNESCO world heritage), Instituto Geofisico (IGEPN - Ecuador's 567

center for both volcanic and seismic monitoring), five hospitals, and two water treatment plants,all of them roughly distributed N-S along the city.

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3.3.3 Merging of the maps

On top of the algorithm described in the previous section, we implemented an additional 573 574 procedure that combines the scenarios of sub-Plinian and Plinian eruption types, weighted according to their probability of occurrence (Fig. 5). The uncertainty distributions of these 575 probabilities have been estimated in Tadini et al. (2021) and are reported in Fig. 2a for Cotopaxi 576 and Fig. 2b for Guagua Pichincha, for both the next eruption and the next 100 years cases. While 577 the former is used in our merging procedure, the second is considered when analyzing the maps 578 related to single eruption types in terms of a comprehensive hazard assessment of the next 100 579 580 years, and it is not used in this section.

In more detail, in case of two eruption types a and b (Fig. 5), for each thickness threshold, 581 the procedure illustrated in section 3.3.1 provides two sets of three output maps (Lower, Natural 582 and Upper). Each map is composed of a series of nodes $(N_{x,y}^L, N_{x,y}^N)$ and $N_{x,y}^U$ for the Lower, 583 Natural and Upper, respectively) that describe the probability *P* of exceeding a certain thickness. 584 The goal of our merging procedure is to combine the probabilities of each node in each map (for 585 our example, $P_{\tau}(N_{x,y}^{L,a})$ and $P_{\tau}(N_{x,y}^{L,b})$ for the Lower; same for Natural and Upper) according to the 586 probabilities P(a) and P(b) that the next eruption will be either a or b. To do so, we initially 587 sample m=1000 probabilities for each eruption type from the probability density functions of the 588 corresponding eruption type of Fig. 2 (next eruption case), which are then normalized to sum to 589 100%. Such probabilities are then used to derive m map sets, where the probability of the node of 590 591 each map is the result of a weighted mean with respect to P(a) and P(b). In other words, for each 592 node we derive a vector composed of *m* elements, each of them resulting from the weighted mean of the original probabilities. Finally, the set of three maps for each thickness threshold 593 594 related to the next eruption (conditional to the occurrence of either eruption a or b) is obtained by sampling, from the vector of each node of the grid: 595

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- for the final Lower map, the 5th percentile of the distribution of the vector;
 - for the final Natural map, the mean (*E*) of the distribution of the vector;
- for the final Upper map, the 95th percentile of the distribution of the vector.

In this way we are able to show the full extent of the uncertainty linked to different eruption types (given by the 5^{th} and 95^{th} percentiles), with a mean value that ultimately represents the actual outputs of the model for each eruption type combined with mean values of eruption occurrences.

As already discussed, this merging procedure has been applied to combine four eruption types of Cotopaxi volcano (sub-Plinian andesitic/rhyolitic and Plinian rhyolitic/andesitic) and two eruption types for Guagua Pichincha volcano (sub-Plinian and Plinian). The same procedure has been used to combine the hazard curves of all the 10 sites.



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616 4 Results and discussion

In the following sub-sections, we present and discuss separately the merged probabilistic 617 and isopach maps and the hazard curves for both Cotopaxi (Figs. 6-8) and Guagua Pichincha 618 (Figs. 9-11) volcanoes. In order to simplify the results (see section 3.3.2), for probability maps 619 we plotted a colored band between upper and lower isolines that highlights both the effects of the 620 uncertainties of the numerical model (see section 3.3.1) and in the probabilities of occurrence of 621 622 the different eruption types considered see section 3.3.3). Instead, for isopach maps we show only the upper isolines to present the worst result in a conservative approach. We also report, in 623 Tables 3-4, the areal extent covered and the population potentially affected by single isopach 624 lines corresponding to 10% and 50% probabilities for both volcanoes. We remark that this is not 625 a risk quantification, which would require a vulnerability assessment that is not the focus of this 626 paper. For the population potentially affected, we have used data from the LandScan database 627 628 (Rose et al., 2020). We stress that some isolines extend further out of the computational domain, and therefore the areas and the population potentially affected represent minimum estimates. 629 Additionally, we include in the supporting information the maps/curves for each single eruption 630 type (Figs. S4-S57) and the calculated exceeding probability values for each accumulation 631 threshold, each eruption type and each sensitive site related to the hazard curves (Table S4). Our 632 results follow a "doubly stochastic" approach, made of two stages. First, we varied the ESPs to 633 produce "classical" hazard maps and curves, and secondly we evaluated the effects of the 634 uncertainties affecting both numerical model and eruption type probability of occurrence. Similar 635 procedures have been applied in pyroclastic density current hazard assessments (Bevilacqua et 636 al., 2017, 2021; Neri et al., 2015; Rutarindwa et al., 2019), but not in the case of an ash fallout 637 hazard assessment. In addition, previous studies did not evaluate the effects of the model 638 uncertainty on the hazard assessments systematically. We remark that our uncertainty assessment 639 highlights how large the uncertainty is, implying that the current knowledge of tephra fallout 640 dispersion and deposition does not allow us to accept or reject previous hazard maps. Those 641 maps are in fact mostly enveloped by our assessments but represent a less complete hazard 642 evaluation because they do not consider all the uncertainty sources that we modeled. Our results 643 644 show that presenting a single volcanic hazard map for a specific eruption probability, would provide an incomplete volcanic hazard assessment. Conversely, presenting a comprehensive set 645 of hazard maps related to the uncertain probabilities of one or more eruption types fully pictures 646 the current available knowledge. If our three maps, i.e. the 5th percentile, the mean, and the 95th 647 percentile values, are considered too complex to be presented to a general audience and/or to be 648 used by the authorities, then only one of them could be used as a reasonable statistical summary 649 650 after a discussion with stakeholders and decision-makers. However, this choice would hide some of the uncertainty to the audience. 651

652 4.1 Cotopaxi

At Cotopaxi, the amount of people potentially affected (especially considering the 50% isolines, see Table 3) is considerable (Figs. 6-7), since seven cities/towns are potentially affected by tephra fall accumulations. Among them, three have > 100,000 inhabitants (Quito, Ambato and Santo Domingo), one has > 25,000 (Latacunga), two have > 5,000 (Machachi and Tena) and one has < 5,000 (Baeza). A striking feature of the maps presented is the drastic changes in people potentially affected within the Lower-Natural-Upper maps.

Considering for instance the 10% isolines (Table 3), for the 10 mm isopach the people potentially affected change from 313,000 (Lower) to more than 4 million (Upper). Concerning the maps themselves, the prevailing winds toward W imply that areas in this direction have higher probabilities of tephra accumulation, which could potentially cause severe issues for both building stability and infrastructures, such as the "Pan-American" highway (see Figs. 6-7 and also Biass & Bonadonna, 2013).

Table 3 can be used for a partial comparison with the work of Biass & Bonadonna 666 (2013), with which our paper shares similarities in the modelling strategy and product outputs, 667 although these authors did not consider the uncertainties in the eruption type probabilities and in 668 the numerical model results. With respect to the areas covered by their 1, 10, 100, 300 kg/m² 669 (roughly comparable to our thickness thresholds) for the 50% probability, our estimated areas are 670 generally in agreement with theirs. For example, in Biass & Bonadonna (2013) the area covered 671 by the 1 kg/m² isomass for an eruption scenario VEI 3-5 for the next 100 years is 7,900 km², 672 while in our Upper (95th percentile) map, the area covered by the 1 mm isopach is 8,777 km² 673 (Table 3). The comparison between our results and those in Biass & Bonadonna (2013) is 674 however complicated by the many methodological differences in i) the model employed, ii) the 675 use of thickness thresholds, iii) the consideration of eruption types rather than single VEIs, and 676 iv) the choice of focusing on the next eruption rather than the next 100 years for combined 677 eruption types (with differences in the estimation of probabilities of occurrence). Nevertheless, 678 further improving the consistency between the elicited values of plume height, the empirical 679 correlation formulas, and the numerical simulator output, within a fully fledged uncertainty 680 assessment is a compelling task for additional research. 681

Considering the impact of tephra accumulation on airports, our maps indicate that two to four airports could be affected by a tephra accumulation of 1 mm with a probability of at least 10% (see Figs. 6 and 7). Among them, Quito international airport (Fig. 8) could have a tephra accumulation of 1 mm and 10 mm of, respectively, 6-27% and 1-14% (Table S4 from the Supporting Information). Such values are in agreement with those proposed by Volentik & Houghton (2015), who calculated the same probabilities as, respectively, 14-20% and 2.5-6%.

Bebbington *et al.* (2008) estimated that an accumulation of 1-2 mm of ash could be sufficient for flashovers to occur along the normal electrical networks, and therefore to cause voltage fluctuations and power shutdown, as also shown by López *et al.* (2016) for Cotopaxi and Tungurahua volcanoes. For Cotopaxi, this accumulation could concern three to five power plants and 329 to 626 km of the electrical network, if we consider, respectively, the lower and upper 10% probability contours (Figs. 6-7).

694 Concerning the sensitive sites in Quito (Figs. 1a and 8), the probabilities for an 695 accumulation of 10 mm (an average of the accumulation thresholds chosen) could be 3-23% for 696 Quito city center (with possible consequences on the cultural heritage), 2-19% for IG-EPN Quito 697 (with possible impact on instrumentation and data transmission systems for volcanic and seismic 698 monitoring), 1-27% for the five hospitals chosen (with possible problems on ventilation and 699 power supply) and 2-20% for the water treatment plants (implying a possible contamination on 700 water supply for the communities).

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Figure 6: Probability maps (Cotopaxi volcano, red triangle) for different thickness accumulations in case the next eruption is sub-Plinian or Plinian. Uppercase letters are city names: A = Ambato, T = Tena, L = Latacunga, M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = El Chaco, C = Cayambe. The extent of the maps is the same as the light blue dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.

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Figure 7: Isopach maps (Cotopaxi volcano, red triangle) for different probabilities in case the next eruption is sub-Plinian or Plinian. Uppercase letters are city names: A = Ambato, T = Tena, L = Latacunga, M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = El Chaco, C =Cayambe. The extent of the maps is the same as the light blue dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.



Figure 8. Hazard curves for 10 sensitive sites in Quito in case the next eruption at Cotopaxi is
 sub-Plinian or Plinian.

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Thickness	Coto A	paxi 10% proba rea Covered (km	bility $\binom{1}{2}$	Cotopaxi 10% probability Population potentially affected		
(mm)	<i>Lower</i> (5 th perc)	Natural (Mean)	Upper (95 th perc)	<i>Lower</i> (5 th perc)	Natural (Mean)	Upper (95 th perc)
1	12,779*	20,444*	25,159*	2,226,274*	4,092,923*	4,390,708*
3	8,495	16,504*	23,257*	1,199,996	3,729,036*	4,234,693*
10	3,649	11,615*	19,080*	313,436	1,987,021*	4,063,216*
30	453	6,348	14,058*	16,041	640,204	2,794,615*
100	-	1,511	7,822	-	101,884	1,130,590
300	-	58	2,411	-	28	183,065
Thickness	Cotopaxi 50% probability Area Covered (km ²)			Cotopaxi 50% probability Population potentially affected		
(mm)	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)
1	1,463	4,230	8,777*	99,641	355,539	1,103,244*
3	348	2,316	6,095	11,204	172,887	509,009
10	-	650	3,346	-	33,819	294,944
30	-	37	1,303	-	8	82,589
100	-	-	70	-	-	41

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Table 3. Area covered and population potentially affected by tephra falls characterized by isopach contours corresponding to 10% and 50% probabilities for next sub-Plinian/Plinian eruption at Cotopaxi volcano. Numbers with * indicate that the corresponding isopach extends out of the computational domain, and the number itself is therefore an underestimation.

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4.2 Guagua Pichincha

745 For Guagua Pichincha volcano, due to the proximity with the highly populated city of Quito, a small variation in the location of an isoline can change significantly the amount of 746 people potentially affected. For example, for the 30 mm isopach line with 10% probability (Figs. 747 9-10), the change in the area covered given by the Lower (5th percentile) and Natural (Mean) 748 maps is roughly 4,300 km² (from ~300 to ~4,600 km²; Table 4), but the amount of people 749 potentially involved changes from 425 to more than 2.7 million. Similar effects are evident also 750 751 for the 100 mm (10% probability) and 3-10 mm (50% probability). We remark that previously existing hazard maps for Guagua Pichincha (see section 2.2) were only semi-probabilistic, thus 752 the comparison with our results is difficult. However, we note that our maps appear to have 753 754 smaller isoline areas, on average, than the previously mentioned assessments. The drastic change in people potentially affected is also linked to the fact that the main direction of wind blowing is 755 toward W (see Figure S1 from the supporting information). This is consequently the main 756 757 direction of isolines elongation, and since the amount of people living in this area is low (due to the presence of the rain forest), the small upwind changes of isoline areas to the E (where Quito 758 759 is located) are the major causes for the drastic changes in the population potentially affected. It is

however important to highlight that the spatial resolution of the meteorological dataset used 760 plays a role in these situations, since different resolutions could cause fluctuations in the position 761 of the isoline resulting in important variations in the population affected. In this study, we have 762 763 chosen a meteorological dataset that optimized the simulation process, but future developments could consider more refined metorological datasets for highly critical areas where it is required 764 an higher degree of accuracy. In general, considering all the isolines and their uncertainties, eight 765 cities/towns might experience different degrees of tephra fall accumulation, three of which with 766 > 100,000 inhabitants (Quito, Ibarra and Santo Domingo), three with > 25,000 (Latacunga, 767 Cayambe and Otavalo), one with > 5,000 (Machachi) and one with < 5,000 (Puerto Ouito). 768

The uncertainty illustrated by the Lower-Natural-Upper maps is also particularly evident 769 with respect to the airports potentially involved. If we focus for example on the 1 mm isopach, 770 only two airports are included within the Lower (5th percentile) 10% isopach, while four are 771 included if we consider the Upper (95th percentile) 10%. For comparison, the Vulcanian 1999 772 eruption of Guagua Pichincha volcano caused an accumulation of 3-5 mm of ash within the old 773 location of Quito airport, and the subsequent closure of the airport for eight days (Guffanti et al., 774 2009). Concerning the new Quito airport, our study provides a specific hazard curve for this site 775 (Fig. 11) with exceeding probabilities (Table S4 from the supporting information). Our 776 probabilities for the 1 mm (25-54%) and 1 cm (7-33%) accumulation are higher than those 777 provided by Volentik & Houghton (2015) (17-20% and 7-8% for the 1 mm and 1 cm, 778 respectively). This is due to the different range of parameters used and the different models 779 employed. 780

Considering the already mentioned threshold of 1-2 mm of ash that could cause electrical 781 flashovers (Bebbington et al., 2008; López et al., 2016) and the maps of Fig. 10, two power 782 plants have 50% probability to have accumulation of 1-3 mm, while another one has 10% 783 probability for the same accumulation. Electric lines concerned by an accumulation of 1 mm are 784 785 at least 416 to 542 km long considering, respectively, the lower and upper isoline of the 10% (Fig. 9) For comparison, during the 1999 eruption of Guagua Pichincha that caused < 5 mm786 accumulation of ash in Ouito, the local thermal power stations stopped their activity as a 787 precautionary measure (d'Ercole & Metzger, 2000). 788

Specifically for the city of Quito, a sub-Plinian to Plinian eruption could lead to ash accumulation of 1 cm with probabilities for the analyzed sites (Figs. 1a and 11 and Table S4 from the supporting information) of i) 13-49% for the five hospitals, ii) 17-58% for city center, iii) 14-50% for IGEPN Quito and iv) 15-57% for the two water treatment plants. With respect to the latter, we recall that, during the 1999 eruption of Guagua Pichincha, a treatment plant in Quito had to be closed due to possible water contamination (d'Ercole & Metzger, 2000).



Figure 9: Probability maps (Guagua Pichincha volcano, red triangle) for different thickness accumulations in case the next eruption is sub-Plinian or Plinian. Uppercase letters are city names: L = Latacunga, M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = ElChaco, C = Cayambe, PQ = Puerto Quito, O = Otavalo, I = Ibarra. The extent of the maps is the same as the light green dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.

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Figure 10: Isopach maps (Guagua Pichincha volcano, red triangle) for different probabilities in
case the next eruption is sub-Plinian or Plinian. Uppercase letters are city names: L =Latacunga,
M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = El Chaco, C = Cayambe, PQ
Puerto Quito, O = Otavalo, I = Ibarra. The extent of the maps is the same as the light green
dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.



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Figure 11. Hazard curves for 10 sensitive sites in Quito in case the next eruption at Guagua Pichincha is sub-Plinian or Plinian.

Thickness	Guagua Pichincha 10% probability Area Covered (km ²)			Guagua Pichincha 10% probability Population potentially affected		
(mm)	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)	<i>Lower</i> (5 th perc)	Natural (Mean)	Upper (95 th perc)
1	11,738*	18,683*	23,817*	3,353,093*	3,777,905*	4,135,175*
3	7,531	14,791*	21,144*	3,233,957	3,480,078*	3,893,651*
10	2,971	9,862*	16,483*	2,364,324	3,307,296*	3,664,184*
30	311	4,678	11,621*	425	2,705,155	3,350,045*
100	-	571	5,229	-	1,502	2,739,530
300	-	26	657	-	22	2,213
Thickness	Guagua Pichincha 50% probability Area Covered (km ²)			Guagua Pichincha 50% probability Population potentially affected		
(mm)	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)
1	1,249	3,368	6,955	152,655	2,285,577	3,145,383
3	315	1,757	4,538	387	1,506,818	2,690,885
10	8	417	2,225	4	925	1,886,192
30	-	25	605	-	21	1,552
100	-	-	26	-	-	19

Table 4. Area covered and population potentially affected by tephra falls characterized by isopach contours corresponding to 10% and 50% probabilities for next sub-Plinian/Plinian eruption at Guagua Pichincha volcano. Numbers with * indicate that the corresponding isopach extends out of the computational domain, and the number itself is therefore an underestimation.

819 **5 Conclusions**

This paper presents a tephra fallout hazard assessment for Cotopaxi and Guagua 820 Pichincha volcanoes as well as an evaluation of the exposure of different sites and infrastructures 821 in the region, with a specific focus on the consequences for the city of Quito. The results include 822 probabilistic maps (for a fixed tephra accumulation and a fixed probability) and hazard curves 823 for 10 sensitive sites in the city of Quito (airport, hospitals, city center, Instituto Geofisico, water 824 treatment plants), related to the specific case that the next eruption at both volcanoes could be 825 either sub-Plinian or Plinian (VEI 3-5). Our new uncertainty quantification procedure has 826 introduced, for all the eruption types and for both volcanoes, set of maps in which each isoline 827 produced from the model output ("Natural") is corrected by producing two additional isolines 828 that take into account model underestimation ("Upper") and overestimation ("Lower"). Our 829 approach is relatively simple and straightforward, and we acknowledge that more studies are 830 needed to refine the definition of the coefficients we used. For example, the tendency of the 831 model to overestimate is greater than its tendency to underestimate, but this is mostly due to the 832 overestimation of the model along the main dispersal axis: future studies could be possibly 833 devoted to find a weighting scheme in the definition of the mean overestimation/underestimation 834 that takes into account this tendency. For both volcanoes, the impacted area, the population and 835

the sensitive sites affected could vary significantly if these three isolines are considered. While some sources of uncertainty could be reduced due better-constrained the input parameters and by improving the modelling features of PLUME-MoM/HYSPLIT, we chose to show the current capabilities of the model by considering the model uncertainty in its widest range (i.e. considering correction coefficients from the worst simulated test eruption). Apart from hazard implications discussed in the previous sections, in our study:

- we have employed a coupling between a plume model (PLUME-MoM) and a tephra 842 transport and dispersal model (HYSPLIT). HYSPLIT is currently used by several Volcanic 843 Ash Advisory Centers (VAACs) and, to the best of our knowledge, has never been used so 844 far to produce isopach tephra fallout hazard maps. Further employments of HYSPLIT for 845 hazard maps production are advisable in order to find solutions for reducing its 846 computational times and therefore considering larger computational domains and/or more 847 refined computational grids. In this work, we have employed the GDAS meteorological 848 dataset, with a spatial resolution of $1^{\circ}x1^{\circ}$ and a temporal resolution of 3 hours. While 849 differences in the final results (i.e. hazard maps) could be only partial if another 850 meteorological dataset was used (due to the many other sources of uncertainty detailed in this 851 study), future developments could also take advantage of more recently released databases 852 (e.g. ERA5), especially for critical areas where even a small shift in the position of an isoline 853 could cause important consequences (see below); 854
- as sampling strategy, we chose to derive (for each eruption) sets of eruptive source 855 ٠ parameters (duration, total mass of tephra fallout and plume height) physically consistent 856 with real eruptions. We used the relations of Mastin et al. (2009) to calculate from one (or 857 two) parameter(s) sampled the remaining two (or one). This procedure introduced 858 correlations between the ESPs, but, as shown in section 3.3.1, also introduced some 859 variations in the original sampling distributions. While such new distributions are within 860 physically coherent ranges, other existing relations (e.g., Sparks et al., 1997) could be 861 employed to evaluate their effect on this recalculation. 862
- We performed the uncertainty quantification in two stages. First, by varying eruptive source 863 parameters to produce "classical" hazard maps and curves, and then evaluating the effects of 864 the uncertainties affecting both numerical model and eruption type probability of occurrence. 865 This "doubly stochastic" approach increases the complexity of the final products, but the 866 effects of the considered sources of uncertainty are significant and should not be averaged or 867 neglected. In fact, even small shifts in the position of isolines can imply a significant change 868 in the amount of people potentially affected by a given tephra accumulation, which has a 869 direct implication in both emergency and long-term planning. 870
- 871 Appendix: total grain-size distribution

Following Costa *et al.* (2016a), the total-grain size distribution is here considered to be composed of two log-normal distributions (i.e. Gaussian in Φ scale) with the form

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$$f_{bi-Gauss}(\Phi) = p \frac{1}{\sigma_1 \sqrt{2\pi}} exp \left[-\frac{(\Phi - \mu_1)}{2\sigma_1^2} \right] + (1 - p) \frac{1}{\sigma_2 \sqrt{2\pi}} exp \left[-\frac{(\Phi - \mu_2)}{2\sigma_2^2} \right]$$
(6)

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where μ_1 , μ_2 and σ_1 , σ_2 are respectively the mean and standard deviations of the two Gaussian distributions in distributions in Φ units, while p is the weight of each sub-population. Empirical values to calculate these parameters have been proposed by the same authors and have beenadapted to our study in the following form

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 $\mu_1 + 3\sigma_1 \approx 0.96 + 0.20H$

 $\sigma_1 \approx 0.67 + 0.07 H$

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 $p = 1.61 \exp(-0.31 Log_{10} \eta)$

 $\mu_2 - \mu_1 \approx 1.62 (Log_{10}\eta)^{0.66}$

with H the plume height (km) and η the magma dynamic viscosity (Pa s).

888

889 Acknowledgments

 $\sigma_2 \approx 1.46$

The simulations have been performed on the cluster of the Laboratoire de Mathématiques Blaise 890 Pascal and on the supercomputer facilities of the Mésocentre at Université Clermont Auvergne. 891 892 We thank Damien Ferney for technical assistance, two anonymous reviewers for their constructive comments that improved the quality of the manuscript, an anonymous Associate 893 Editor, and Editor in chief Isabelle Manighetti for editorial handling. This research was financed 894 by the French government IDEX-ISITE initiative 16-IDEX-0001 (CAP 20-25), the French 895 Research Institute for Sustainable Development (IRD) in the context of the Laboratoire Mixte 896 International "Séismes et Volcans dans les Andes du Nord" (collaboration between IG-EPN 897 898 Quito and LMV Clermont-Ferrand), and the CNRS Tellus programme. This work was also partly funded by the ClerVolc project - Programme 1 "Detection and characterization of volcanic 899 plumes and ash clouds" funded by the French government 'Laboratory of Excellence' initiative. 900 This is Clervolc contribution number XXX. 901

- ⁹⁰² The authors have no competing interests to declare.
- Data supporting the analyses and conclusions presented in this study could be found in a repository in the Figshare community with the following DOI:
- 905 https://figshare.com/s/d039d9c741040b70c88c
- 906

907 **References**

- Alpízar Segura, Y., M. Fernández Arce, C. Ramírez Umaña, & D. Arroyo Alpízar (2019), Hazard Map of Rincón de la Vieja Volcano, Costa Rica: Qualitative Integration of Computer Simulations and Geological Data, *Anuario do Instituto de Geociencias*, 42(3), doi:<u>http://dx.doi.org/10.11137/2019_3_474_488</u>.
- Andújar, J., C. Martel, M. Pichavant, P. Samaniego, B. Scaillet, & I. Molina (2017), Structure of the plumbing
 system at Tungurahua volcano, Ecuador: insights from phase equilibrium experiments on July–August
 2006 eruption products, *Journal of Petrology*, 58(7), 1249-1278,
 doi:https://doi.org/10.1093/petrology/egx054.
- Annen, C., & J. J. Wagner (2003), The impact of volcanic eruptions during the 1990s, *Natural Hazards Review*,
 4(4), 169-175, doi:https://doi.org/10.1061/(ASCE)1527-6988(2003)4:4(169).
- Armienti, P., G. Macedonio, & M. T. Pareschi (1988), A numerical model for simulation of tephra transport and
 deposition: Applications to May 18, 1980, Mount St. Helens eruption, *Journal of Geophysical Research: Solid Earth*, 93(B6), 6463-6476, doi:https://doi.org/10.1029/JB093iB06p06463.

- Aspinall, W. P. (2006), Structured elicitation of expert judgment for probabilistic hazard and risk assessment in
 volcanic eruptions, *Statistics in volcanology*, *1*, 15-30.
- Aspinall, W. P., A. Bevilacqua, A. Costa, H. Inakura, S. Mahony, A. Neri, & R. S. J. Sparks (2019), Probabilistic
 reconstruction (or forecasting) of distal runouts of large magnitude ignimbrite PDC flows sensitive to
 topography using mass-dependent inversion models, paper presented at AGU Fall Meeting 2019, San
 Francisco, CA, USA.
- Barberi, F., M. Coltelli, A. Frullani, M. Rosi, & E. Almeida (1995), Chronology and dispersal characteristics of
 recently (last 5000 years) erupted tephra of Cotopaxi (Ecuador): implications for long-term eruptive
 forecasting, *Journal of Volcanology and Geothermal research*, 69(3-4), 217-239,
 doi:https://doi.org/10.1016/0377-0273(95)00017-8.
- Barberi, F., M. Ghigliotti, G. Macedonio, H. Orellana, M. T. Pareschi, & M. Rosi (1992), Volcanic hazard
 assessment of Guagua Pichincha (Ecuador) based on past behaviour and numerical models, *J. Volcanol. Geoth. Res.*, 49(1-2), 53-68, doi:https://doi.org/10.1016/0377-0273(92)90004-W.
- Barberi, F., G. Macedonio, M. T. Pareschi, & R. Santacroce (1990), Mapping the tephra fallout risk: an example
 from Vesuvius, Italy, *Nature*, *344*(6262), 142-144.
- Barsotti, S., D. I. Di Rienzo, T. Thordarson, B. B. Björnsson, & S. Karlsdóttir (2018), Assessing impact to
 infrastructures due to tephra fallout from Öræfajökull volcano (Iceland) by using a scenario-based approach
 and a numerical model, *Frontiers in Earth Science*, 6, 196, doi:https://doi.org/10.3389/feart.2018.00196.
- Barsotti, S., & A. Neri (2008), The VOL-CALPUFF model for atmospheric ash dispersal: 2. Application to the weak
 Mount Etna plume of July 2001, *Journal of Geophysical Research: Solid Earth*, *113*(B3),
 doi:https://doi.org/10.1029/2006JB004624.
- Barsotti, S., A. Neri, & J. S. Scire (2008), The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach
 and physical formulation, *Journal of Geophysical Research: Solid Earth*, *113*(B3),
 doi:https://doi.org/10.1029/2006JB004623.
- Baxter, P. J. (1990), Medical effects of volcanic eruptions, *Bulletin of Volcanology*, 52(7), 532-544,
 doi:https://doi.org/10.1007/BF00301534.
- Baxter, P. J., & C. J. Horwell (2015), Impacts of eruptions on human health, in *The encyclopedia of volcanoes*,
 edited by H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer and J. Stix, pp. 1035-1047, Elsevier,
 doi:https://doi.org/10.1016/B978-0-12-385938-9.00060-2.
- Bebbington, M. S., S. J. Cronin, I. Chapman, & M. B. Turner (2008), Quantifying volcanic ash fall hazard to
 electricity infrastructure, *Journal of Volcanology and Geothermal Research*, *177*(4), 1055-1062,
 doi:https://doi.org/10.1016/j.jvolgeores.2008.07.023.
- Bernard, B., J. Battaglia, A. Proaño, S. Hidalgo, F. Vásconez, S. Hernandez, & M. C. Ruiz (2016), Relationship
 between volcanic ash fallouts and seismic tremor: quantitative assessment of the 2015 eruptive period at
 Cotopaxi volcano, Ecuador, *Bull. Volc.*, 78(11), doi:10.1007/s00445-016-1077-5.
- Bevilacqua, A., A. Aravena, A. Neri, E. Gutiérrez, D. Escobar, M. Schliz, et al. (2021), Thematic vent opening
 probability maps and hazard assessment of small-scale pyroclastic density currents in the San Salvador
 volcanic complex (El Salvador) and Nejapa-Chiltepe volcanic complex (Nicaragua), *Natural Hazards and Earth System Sciences*, 21(5), 1639-1665, doi:https://doi.org/10.5194/nhess-21-1639-2021.
- Bevilacqua, A., A. Bertagnini, M. Pompilio, P. Landi, P. Del Carlo, A. Di Roberto, et al. (2020), Major explosions
 and paroxysms at Stromboli (Italy): a new historical catalog and temporal models of occurrence with
 uncertainty quantification, *Scientific Reports*, *10*, doi:https://doi.org/10.1038/s41598-020-74301-8.
- Bevilacqua, A., M. I. Bursik, A. K. Patra, B. E. Pitman, Q. Yang, R. Sangani, & S. Kobs-Nawotniak (2018), Late
 Quaternary eruption record and probability of future volcanic eruptions in the Long Valley volcanic region
 (CA, USA), *Journal of Geophysical Research: Solid Earth*, *123*(7), 5466-5494,
 doi:https://doi.org/10.1029/2018JB015644.
- Bevilacqua, A., F. Flandoli, A. Neri, R. Isaia, & S. Vitale (2016), Temporal models for the episodic volcanism of
 Campi Flegrei caldera (Italy) with uncertainty quantification, *Journal of Geophysical Research: Solid Earth*, 121(11), 7821-7845, doi:https://doi.org/10.1002/2016JB013171.
- Bevilacqua, A., R. Isaia, A. Neri, S. Vitale, W. P. Aspinall, M. Bisson, et al. (2015), Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: I. Vent opening maps, *Journal of Geophysical Research: Solid Earth*, *120*, 2309-2329, doi:https://doi.org/10.1002/2014JB011775.
- Bevilacqua, A., A. Neri, M. Bisson, T. Esposti Ongaro, F. Flandoli, R. Isaia, et al. (2017), The effects of vent
 location, event scale, and time forecasts on pyroclastic density current hazard maps at Campi Flegrei
 caldera (Italy), *Frontiers in Earth Science*, 5, 72, doi:https://doi.org/10.3389/feart.2017.00072.

- Bevilacqua, A., A. K. Patra, M. I. Bursik, E. B. Pitman, J. L. Macías, R. Saucedo, & D. Hyman (2019), Probabilistic
 forecasting of plausible debris flows from Nevado de Colima (Mexico) using data from the Atenquique
 debris flow, 1955, *Natural Hazard and Earth System Sciences*, *19*(4), doi:https://doi.org/10.5194/nhess-19791-2019.
- Biass, S., & C. Bonadonna (2011), A quantitative uncertainty assessment of eruptive parameters derived from tephra deposits: the example of two large eruptions of Cotopaxi volcano, Ecuador, *Bulletin of Volcanology*, 73(1), 73-90.
- Biass, S., & C. Bonadonna (2013), A fast GIS-based risk assessment for tephra fallout: the example of Cotopaxi volcano, Ecuador, *Natural Hazards*, 65(1), 477-495, doi:https://doi.org/10.1007/s11069-012-0378-z.
- Biass, S., C. Frischknecht, & C. Bonadonna (2013), A fast GIS-based risk assessment for tephra fallout: the example
 of Cotopaxi volcano, Ecuador Part II: vulnerability and risk assessment, *Natural hazards*, 65(1), 497-521,
 doi:https://doi.org/10.1007/s11069-012-0457-1.
- Biass, S., C. Scaini, C. Bonadonna, A. Folch, K. Smith, & A. Höskuldsson (2014), A multi-scale risk assessment for
 tephra fallout and airborne concentration from multiple Icelandic volcanoes-Part 1: Hazard assessment,
 Natural Hazards and Earth System Sciences, *14*(8), 2265, doi:10.5194/nhess-14-2265-2014.
- Blake, D. M., T. M. Wilson, J. W. Cole, N. I. Deligne, & J. M. Lindsay (2017), Impact of volcanic ash on road and airfield surface skid resistance, *Sustainability*, 9(8), 1389, doi:https://doi.org/10.3390/su9081389.
- Blong, R. J. (1996), Volcanic hazards risk assessment, in *Monitoring and mitigation of volcano hazards*, edited by
 R. Scarpa and R. I. Tilling, pp. 675-698, Springer, Berlin.
- Bonadonna, C. (2006), Probabilistic modelling of tephra dispersion, in *Statistics in Volcanology*, edited by H. M.
 Mader, S. G. Coles, C. B. Connor and L. J. Connor, pp. 243-259, Geological Society, London.
- Bonadonna, C., R. Cioni, M. Pistolesi, M. Elissondo, & V. Baumann (2015a), Sedimentation of long-lasting windaffected volcanic plumes: the example of the 2011 rhyolitic Cordón Caulle eruption, Chile, *Bulletin of Volcanology*, 77(2), 13.
- Bonadonna, C., C. B. Connor, B. F. Houghton, L. J. Connor, M. Byrne, A. Laing, & T. K. Hincks (2005),
 Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand, *Journal of Geophysical Research: Solid Earth*, *110*(B3),
 doi:https://doi.org/10.1029/2003JB00289.
- Bonadonna, C., & J. C. Phillips (2003), Sedimentation from strong volcanic plumes, *Journal of Geophysical Research: Solid Earth*, 108(B7), doi:https://doi.org/10.1029/2002JB002034.
- Bonadonna, C., M. Pistolesi, R. Cioni, W. Degruyter, M. Elissondo, & V. Baumann (2015b), Dynamics of wind affected volcanic plumes: The example of the 2011 Cordón Caulle eruption, Chile, *Journal of Geophysical Research: Solid Earth*, 120(4), 2242-2261.
- Bonasia, R., L. Capra, A. Costa, G. Macedonio, & R. Saucedo (2011), Tephra fallout hazard assessment for a
 Plinian eruption scenario at Volcán de Colima (Mexico), *Journal of Volcanology and Geothermal Research*, 203(1-2), 12-22, doi:https://doi.org/10.1016/j.jvolgeores.2011.03.006.
- Brown, S. K., S. F. Jenkins, R. S. J. Sparks, H. Odbert, & M. R. Auker (2017), Volcanic fatalities database: analysis
 of volcanic threat with distance and victim classification, *Journal of Applied Volcanology*, 6(1), 1-20,
 doi:https://doi.org/10.1186/s13617-017-0067-4.
- Budd, L., S. Griggs, D. Howarth, & S. Ison (2011), A fiasco of volcanic proportions? Eyjafjallajökull and the
 closure of European airspace, *Mobilities*, 6(1), 31-40, doi:https://doi.org/10.1080/17450101.2011.532650.
- Bursik, M. I. (2001), Effect of wind on the rise height of volcanic plumes, *Geophysical Research Letters*, 28(18),
 3621-3624, doi:https://doi.org/10.1029/2001GL013393.
- Bursik, M. I., M. Jones, S. Carn, K. Dean, A. K. Patra, M. Pavolonis, et al. (2012), Estimation and propagation of volcanic source parameter uncertainty in an ash transport and dispersal model: application to the Eyjafjallajokull plume of 14–16 April 2010, *Bulletin of volcanology*, 74(10), 2321-2338, doi:https://doi.org/10.1007/s00445-012-0665-2.
- Bursik, M. I., S. E. Kobs, A. Burns, O. A. Braitseva, L. I. Bazanova, I. V. Melekestsev, et al. (2009), Volcanic
 plumes and wind: Jetstream interaction examples and implications for air traffic, *Journal of Volcanology and Geothermal Research*, *186*(1-2), 60-67, doi:https://doi.org/10.1016/j.jvolgeores.2009.01.021.
- Capra, L., G. Norini, G. Groppelli, J. L. Macías, & J. L. Arce (2008), Volcanic hazard zonation of the Nevado de Toluca volcano, México, *Journal of Volcanology and Geothermal Research*, *176*(4), 469-484, doi:https://doi.org/10.1016/j.jvolgeores.2008.04.016.
- Cioni, R., A. Longo, G. Macedonio, R. Santacroce, A. Sbrana, R. Sulpizio, & D. Andronico (2003), Assessing
 pyroclastic fall hazard through field data and numerical simulations: example from Vesuvius, *Journal of Geophysical Research: Solid Earth (1978–2012), 108*(B2), 2063.

- 1031 Cooke, R. M. (1991), Experts in uncertainty: opinion and subjective probability in science.
- Costa, A., F. Dell'Erba, M. A. Di Vito, R. Isaia, G. Macedonio, G. Orsi, & T. Pfeiffer (2009), Tephra fallout hazard
 assessment at the Campi Flegrei caldera (Italy), *Bulletin of Volcanology*, 71(3), 259,
 doi:https://doi.org/10.1007/s00445-008-0220-3.
- Costa, A., G. Macedonio, & A. Folch (2006), A three-dimensional Eulerian model for transport and deposition of
 volcanic ashes, *Earth and Planetary Science Letters*, 241(3-4), 634-647,
 doi:https://doi.org/10.1016/j.epsl.2005.11.019.
- Costa, A., L. Pioli, & C. Bonadonna (2016a), Assessing tephra total grain-size distribution: Insights from field data analysis, *Earth and Planetary Science Letters*, 443, 90-107, doi:https://doi.org/10.1016/j.epsl.2016.02.040.
- Costa, A., Y. J. Suzuki, M. Cerminara, B. J. Devenish, T. Esposti Ongaro, M. Herzog, et al. (2016b), Results of the
 eruptive column model inter-comparison study, *Journal of Volcanology and Geothermal Research*, 326, 2 doi:https://doi.org/10.1016/j.jvolgeores.2016.01.017.
- d'Ercole, R., & P. Metzger (2000), La vulnérabilité de Quito (Equateur) face à l'activité du Guagua Pichincha. Les
 premières leçons d'une crise volcanique durable, *Cahiers Savoisiens de Géographie*, 1, 39-52,
 doi:https://hal.archives-ouvertes.fr/hal-01196431.
- 1046de' Michieli Vitturi, M., & F. Pardini (2021), PLUME-MoM-TSM 1.0.0: a volcanic column and umbrella cloud1047spreading model, Geoscientific Model Development, 14(3), 1345–1377, doi:https://doi.org/10.5194/gmd-104814-1345-2021.
- de'Michieli Vitturi, M., A. Neri, & S. Barsotti (2015), PLUME-MoM 1.0: A new integral model of volcanic plumes
 based on the method of moments, *Geoscientific Model Development*, 8(8), 2447.
- Ecuatoriana, C. R. (2020), Plan de acción temprana por dispersión de ceniza volcánica. Proyecto Preparación basada
 en Pronósticos*Rep*.
- Eychenne, J., J. L. Le Pennec, L. Troncoso, M. Gouhier, & J. M. Nedelec (2012), Causes and consequences of
 bimodal grain-size distribution of tephra fall deposited during the August 2006 Tungurahua eruption
 (Ecuador), *Bulletin of Volcanology*, 74(1), 187-205, doi:https://doi.org/10.1007/s00445-011-0517-5.
- Flandoli, F., E. Giorgi, W. P. Aspinall, & A. Neri (2011), Comparison of a new expert elicitation model with the
 Classical Model, equal weights and single experts, using a cross-validation technique, *Reliability Engineering & System Safety*, 96(10), 1292-1310, doi:https://doi.org/10.1016/j.ress.2011.05.012.
- Folch, A., A. Costa, & S. Basart (2012), Validation of the FALL3D ash dispersion model using observations of the
 2010 Eyjafjallajökull volcanic ash clouds, *Atmospheric Environment*, 48, 165-183,
 doi:https://doi.org/10.1016/j.atmosenv.2011.06.072.
- Folch, A., A. Costa, & G. Macedonio (2009), FALL3D: A computational model for transport and deposition of
 volcanic ash, *Computers & Geosciences*, *35*(6), 1334-1342,
 doi:https://doi.org/10.1016/j.cageo.2008.08.008.
- Folch, A., L. Mingari, N. Gutierrez, M. Hanzich, G. Macedonio, & A. Costa (2020), FALL3D-8.0: a computational model for atmospheric transport and deposition of particles, aerosols and radionuclides–Part 1: Model physics and numerics, *Geoscientific Model Development*, *13*(3), 1431-1458, doi:https://doi.org/10.5194/gmd-13-1431-2020.
- Folch, A., & R. Sulpizio (2010), Evaluating long-range volcanic ash hazard using supercomputing facilities:
 application to Somma-Vesuvius (Italy), and consequences for civil aviation over the Central Mediterranean
 Area, *Bulletin of Volcanology*, 72(9), 1039-1059, doi:https://doi.org/10.1007/s00445-010-0386-3.
- Garcia-Aristizabal, A., H. Kumagai, P. Samaniego, P. Mothes, H. Yepes, & M. Monzier (2007), Seismic, petrologic, and geodetic analyses of the 1999 dome-forming eruption of Guagua Pichincha volcano, Ecuador, J.
 Volcanol. Geoth. Res., 161(4), 333-351, doi:https://doi.org/10.1016/j.jvolgeores.2006.12.007.
- Gaunt, H. E., B. Bernard, S. Hidalgo, A. Proaño, H. M. Wright, P. Mothes, et al. (2016), Juvenile magma
 recognition and eruptive dynamics inferred from the analysis of ash time series: The 2015 reawakening of
 Cotopaxi volcano, *Journal of Volcanology and Geothermal Research*, *328*, 134-146,
 doi:https://doi.org/10.1016/j.jvolgeores.2016.10.013.
- Guffanti, M., G. C. Mayberry, T. J. Casadevall, & R. Wunderman (2009), Volcanic hazards to airports, *Natural hazards*, 51(2), 287-302, doi:https://doi.org/10.1007/s11069-008-9254-2.
- Hall, M. L., P. Mothes, D. Andrade, P. Samaniego, & H. Yepes (2004a), Mapa regional de peligros volcánicos
 potenciales del volcán Cotopaxi-Zona Sur, IG-EPN, Quito, Ecuador.
- Hall, M. L., P. Mothes, P. Samaniego, H. Yepes, & D. Andrade (2004b), Mapa Regional de Peligros Volcánicos
 Potenciales del Volcán Cotopaxi Zona Norte, IG-EPN, Quito, Ecuador.
- Hall, M. L., & P. A. Mothes (2008), The rhyolitic–andesitic eruptive history of Cotopaxi volcano, Ecuador, *Bulletin* of Volcanology, 70(6), 675-702, doi:https://doi.org/10.1007/s00445-007-0161-2.

- Hall, M. L., & C. G. M. von Hillebrandt (1988a), Mapa de los peligros volcanicos potenciales asociados con el
 volcan Cotopaxi: zona norte and zona sur, IG-EPN, Quito, Ecuador.
- Hall, M. L., & C. G. M. von Hillebrandt (1988b), Mapa de los peligros volcanicos potenciales asociados con el volcan Guagua Pichincha-Provincia de Pichincha, IG-EPN, Quito, Ecuador.
- Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, et al. (2020), The ERA5 global
 reanalysis, Q. J. Roy. Meteor. Soc., 146(730), 1999-2049.
- Hidalgo, S., J. Battaglia, S. Arellano, D. Sierra, B. Bernard, R. Parra, et al. (2018), Evolution of the 2015 Cotopaxi
 eruption revealed by combined geochemical and seismic observations, *Geochemistry, Geophysics, Geosystems, 19*(7), 2087-2108, doi:https://doi.org/10.1029/2018GC007514.
- Hurst, T., & W. Smith (2004), A Monte Carlo methodology for modelling ashfall hazards, *Journal of volcanology* and geothermal research, 138(3-4), 393-403, doi:https://doi.org/10.1016/j.jvolgeores.2004.08.001.
- IG-EPN, IGM, & IRD (2019), Mapa de Peligros Volcánicos Potenciales del Volcán Guagua Pichincha 3ra. Edición,
 Quito Ecuador, Quito Ecuador.
- 1100 Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, et al. (1996), The NCEP/NCAR 40-Year
 1101 Reanalysis Project, *Bull. Am. Met. Soc.*, 77(3), 437-472, doi:10.1175/1520 1102 0477(1996)077<0437:tnyrp>2.0.co;2.
- López, A., J. Ramírez, F. Vásconez, B. Bernard, F. Valencia, S. Hidalgo, et al. (2016), Volcanic ash impacts on the
 dielectric strength of HVAC Outdoor Suspension Insulators: the case of Cotopaxi and Tungurahua
 volcanoes (Ecuador), paper presented at Cities on Volcanoes 9, Puerto Varas, Chile, 20-25/11/2016.
- Macedonio, G., & A. Costa (2012), Brief Communication" Rain effect on the load of tephra deposits", *Natural Hazards and Earth System Sciences*, *12*(4), 1229-1233, doi:https://doi.org/10.5194/nhess-12-1229-2012.
- Macedonio, G., A. Costa, & A. Longo (2005), A computer model for volcanic ash fallout and assessment of
 subsequent hazard, *Computers & Geosciences*, *31*(7), 837-845,
 doi:https://doi.org/10.1016/j.cageo.2005.01.013.
- Macedonio, G., A. Costa, S. Scollo, & A. Neri (2016), Effects of eruption source parameter variation and
 meteorological dataset on tephra fallout hazard assessment: example from Vesuvius (Italy), *Journal of Applied Volcanology*, 5(1), 1.
- Macedonio, G., M. T. Pareschi, & R. Santacroce (1988), A numerical simulation of the Plinian fall phase of 79 AD
 eruption of Vesuvius, *Journal of Geophysical Research: Solid Earth*, 93(B12), 14817-14827.
- Madankan, R., S. Pouget, P. Singla, M. I. Bursik, J. Dehn, M. Jones, et al. (2014), Computation of probabilistic
 hazard maps and source parameter estimation for volcanic ash transport and dispersion, *Journal of Computational Physics*, 271, 39-59, doi:https://doi.org/10.1016/j.jcp.2013.11.032.
- Martel, C., J. Andújar, P. Mothes, B. Scaillet, M. Pichavant, & I. Molina (2018), Storage conditions of the mafic and
 silicic magmas at Cotopaxi, Ecuador, *Journal of Volcanology and Geothermal Research*, 354, 74-86.
- Marzocchi, W., L. Sandri, & J. Selva (2008), BET_EF: a probabilistic tool for long-and short-term eruption
 forecasting, *Bulletin of Volcanology*, 70(5), 623-632, doi:https://doi.org/10.1007/s00445-007-0157-y.
- Marzocchi, W., L. Sandri, & J. Selva (2010), BET_VH: a probabilistic tool for long-term volcanic hazard
 assessment, *Bulletin of Volcanology*, 72(6), 705-716, doi:https://doi.org/10.1007/s00445-010-0357-8.
- Mastin, L. G., M. Guffanti, R. Servranckx, P. Webley, S. Barsotti, K. Dean, et al. (2009), A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions, *Journal of Volcanology and Geothermal Research*, *186*(1-2), 10-21, doi:https://doi.org/10.1016/j.jvolgeores.2009.01.008.
- Mastin, L. G., A. R. Van Eaton, D. Schneider, & R. P. Denlinger (2017), Ongoing Efforts to Make Ash-Cloud
 Model Forecasts More Accurate*Rep.*, NATO Science and Technology Organization.
- Miller, C. D., D. R. Mullineaux, & M. L. Hall (1978), Reconnaissance Map of Potential Volcanic Hazards from
 Cotopaxi Volcano, Ecuador: Mapa de Reconocimiento de Riesgos Volganicos Potenciales Del Volcan
 Cotopaxi, Ecuador, US Geological Survey.
- Mothes, P. A., P. Espin, M. L. Hall, F. Vasconez, D. Sierra, & D. Andrade (2016a), Mapa regional de amenazas
 volcánicas potenciales del volcán Cotopaxi, zona Norte, Quito.
- Mothes, P. A., P. Espin, M. L. Hall, F. Vasconez, D. Sierra, & D. Andrade (2016b), Mapa regional de amenazas
 volcánicas potenciales del volcán Cotopaxi, zona Sur, Quito.
- Neri, A., W. P. Aspinall, R. Cioni, A. Bertagnini, P. J. Baxter, G. Zuccaro, et al. (2008), Developing an event tree for probabilistic hazard and risk assessment at Vesuvius, *Journal of Volcanology and Geothermal Research*, *178*(3), 397-415, doi:https://doi.org/10.1016/j.jvolgeores.2008.05.014.

1141 Neri, A., A. Bevilacqua, T. Esposti Ongaro, R. Isaia, W. P. Aspinall, M. Bisson, et al. (2015), Quantifying volcanic 1142 hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: II. Pyroclastic density current invasion 1143 maps, Journal of Geophysical Research: Solid Earth, doi:https://doi.org/10.1002/2014JB011776. 1144 NOAA (2004), Global Data Assimilation System (GDAS1) Archive Information, edited, 1145 doi:https://www.ready.noaa.gov/gdas1.php. 1146 Orsi, G., M. A. Di Vito, & R. Isaia (2004), Volcanic hazard assessment at the restless Campi Flegrei caldera, Bulletin of Volcanology, 66(6), 514-530, doi:https://doi.org/10.1007/s00445-003-0336-4. 1147 1148 Pardini, F., S. Corradini, A. Costa, T. Esposti Ongaro, L. Merucci, A. Neri, & D. Stelitano (2020), Ensemble-Based 1149 Data Assimilation of Volcanic Ash Clouds from Satellite Observations: Application to the 24 December 1150 2018 Mt. Etna Explosive Eruption, Atmosphere, 11(4), 359, doi:https://doi.org/10.3390/atmos11040359. Patra, A. K., A. Bevilacqua, A. Akhavan-Safaei, E. B. Pitman, M. I. Bursik, & D. Hyman (2020), Comparative 1151 1152 analysis of the structures and outcomes of geophysical flow models and modeling assumptions using 1153 uncertainty quantification, Frontiers in Earth Science, doi:10.3389/feart.2020.00275. 1154 Patra, A. K., A. Bevilacqua, & A. A. Safei (2018), Analyzing Complex Models using Data and Statistics, paper 1155 presented at International Conference on Computational Science, Springer. 1156 Pistolesi, M., M. Rosi, R. Cioni, K. V. Cashman, A. Rossotti, & E. Aguilera (2011), Physical volcanology of the 1157 post-twelfth-century activity at Cotopaxi volcano, Ecuador: Behavior of an andesitic central volcano, Geol. 1158 Soc. Am. Bull., 123(5-6), 1193-1215, doi:https://doi.org/10.1130/B30301.1. 1159 Pouget, S., M. I. Bursik, P. Singla, & T. Singh (2016), Sensitivity analysis of a one-dimensional model of a volcanic 1160 plume with particle fallout and collapse behavior, Journal of Volcanology and Geothermal Research, 326, 1161 43-53, doi:https://doi.org/10.1016/j.jvolgeores.2016.02.018. Prata, A. T., L. Mingari, A. Folch, G. Macedonio, & A. Costa (2021), FALL3D-8.0: a computational model for 1162 1163 atmospheric transport and deposition of particles, aerosols and radionuclides-Part 2: model validation, Geoscientific Model Development, 14(1), 409-436, doi:https://doi.org/10.5194/gmd-14-409-2021. 1164 1165 Riley, C. M., W. I. Rose, & G. J. S. Bluth (2003), Quantitative shape measurements of distal volcanic ash, Journal 1166 of Geophysical Research: Solid Earth, 108(B10), doi:https://doi.org/10.1029/2001JB000818. Robin, C., P. Samaniego, J. L. Le Pennec, M. Fornari, P. Mothes, & J. Van Der Plicht (2010), New radiometric and 1167 1168 petrological constraints on the evolution of the Pichincha volcanic complex (Ecuador), Bulletin of 1169 volcanology, 72(9), 1109-1129, doi:https://doi.org/10.1007/s00445-010-0389-0. 1170 Robin, C., P. Samaniego, J. L. Le Pennec, P. Mothes, & J. van der Plicht (2008), Late Holocene phases of dome 1171 growth and Plinian activity at Guagua Pichincha volcano (Ecuador), Journal of Volcanology and Geothermal Research, 176(1), 7-15, doi:https://doi.org/10.1016/j.jvolgeores.2007.10.008. 1172 1173 Rose, A. N., J. J. McKee, K. M. Sims, E. A. Bright, A. E. Reith, & M. L. Urban (2020), LandScan 2019, edited, Oak 1174 Ridge National Laboratory, Oak Ridge, TN, doi:https://landscan.ornl.gov/. 1175 Rutarindwa, R., E. T. Spiller, A. Bevilacqua, M. I. Bursik, & A. K. Patra (2019), Dynamic probabilistic hazard 1176 mapping in the Long Valley Volcanic Region CA: integrating vent opening maps and statistical surrogates 1177 of physical models of pyroclastic density currents, J. Geophys. Res.-Sol. Ea. 1178 Samaniego, P., C. Robin, G. Chazot, E. Bourdon, & J. Cotten (2010), Evolving metasomatic agent in the Northern 1179 Andean subduction zone, deduced from magma composition of the long-lived Pichincha volcanic complex 1180 (Ecuador), Contributions to Mineralogy and Petrology, 160(2), 239-260, 1181 doi:https://doi.org/10.1007/s00410-009-0475-5. 1182 Sandri, L., A. Costa, J. Selva, R. Tonini, G. Macedonio, A. Folch, & R. Sulpizio (2016), Beyond eruptive scenarios: 1183 assessing tephra fallout hazard from Neapolitan volcanoes, Scientific reports, 6(1), 1-13, 1184 doi:https://doi.org/10.1038/srep24271. 1185 Scaini, C., A. Folch, & M. Navarro (2012), Tephra hazard assessment at Concepción Volcano, Nicaragua, Journal 1186 of volcanology and geothermal research, 219, 41-51, doi:https://doi.org/10.1016/j.jvolgeores.2012.01.007. 1187 Schwaiger, H. F., R. P. Denlinger, & L. G. Mastin (2012), Ash3d: A finite-volume, conservative numerical model 1188 for ash transport and tephra deposition, Journal of Geophysical Research: Solid Earth, 117(B4), 1189 doi:https://doi.org/10.1029/2011JB008968. 1190 Scollo, S., S. Tarantola, C. Bonadonna, M. Coltelli, & A. Saltelli (2008), Sensitivity analysis and uncertainty 1191 estimation for tephra dispersal models, Journal of Geophysical Research: Solid Earth, 113(B6), 1192 doi:https://doi.org/10.1029/2006JB004864. Sparks, R. S. J., M. I. Bursik, S. N. Carey, J. S. Gilbert, L. S. Glaze, H. Sigurdsson, & A. W. Woods (1997), 1193 1194 Volcanic plumes, Wiley.

- Spence, R. J. S., I. Kelman, P. J. Baxter, G. Zuccaro, & S. Petrazzuoli (2005), Residential building and occupant
 vulnerability to tephra fall, *Natural Hazards and Earth System Sciences*, 5(4), 477-494,
 doi:https://doi.org/10.5194/nhess-5-477-2005.
- Spera, F. J. (2000), Physical properties of magma, in *Encyclopedia on Volcanoes*, edited by H. Sigurdsson, B. F.
 Houghton, S. R. McNutt, H. Rymer and J. Stix, Academic Press, San Diego, CA.
- Stefanescu, E. R., A. K. Patra, M. I. Bursik, R. Madankan, S. Pouget, M. Jones, et al. (2014), Temporal,
 probabilistic mapping of ash clouds using wind field stochastic variability and uncertain eruption source
 parameters: Example of the 14 A pril 2010 E yjafjallajökull eruption, *Journal of Advances in Modeling Earth Systems*, 6(4), 1173-1184, doi:https://doi.org/10.1002/2014MS000332.
- Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, & F. Ngan (2015), NOAA's HYSPLIT
 atmospheric transport and dispersion modeling system, *Bulletin of the American Meteorological Society*, 96(12), 2059-2077.
- Tadini, A., A. Bevilacqua, A. Neri, R. Cioni, W. P. Aspinall, M. Bisson, et al. (2017a), Assessing future vent
 opening locations at the Somma-Vesuvio volcanic complex: 2. Probability maps of the caldera for a future
 Plinian/sub-Plinian event with uncertainty quantification, *Journal of Geophysical Research: Solid Earth*,
 122(6), 4357-4376, doi:10.1002/2016JB013860.
- Tadini, A., M. Bisson, A. Neri, R. Cioni, A. Bevilacqua, & W. P. Aspinall (2017b), Assessing future vent opening
 locations at the Somma-Vesuvio volcanic complex: 1. A new information geo-database with uncertainty
 characterizations, *Journal of Geophysical Research: Solid Earth*, *122*(6), 4336-4356,
 doi:10.1002/2016JB013858.
- Tadini, A., O. Roche, P. Samaniego, N. Azzaoui, A. Bevilacqua, A. Guillin, et al. (2021), Eruption type probability
 and eruption source parameters at Cotopaxi and Guagua Pichincha volcanoes (Ecuador) with uncertainty
 quantification, *Bullettin of Volcanology*, *83*(35), doi:https://doi.org/10.1007/s00445-021-01458-z.
- Tadini, A., O. Roche, P. Samaniego, A. Guillin, N. Azzaoui, M. Gouhier, et al. (2020), Quantifying the uncertainty
 of a coupled plume and tephra dispersal model: PLUME-MOM/HYSPLIT simulations applied to Andean
 volcanoes, *Journal of Geophysical Research: Solid Earth*, *125*(2),
 doi:https://doi.org/10.1029/2019JB018390.
- Tsuji, T., M. Ikeda, H. Kishimoto, K. Fujita, N. Nishizaka, & K. Onishi (2017), Tephra Fallout Hazard Assessment
 for VEI5 Plinian Eruption at Kuju Volcano, Japan, Using TEPHRA2, paper presented at IOP Conference
 Series: Earth and Environmental Science, IOP Publishing.
- 1225Tsunematsu, K., & C. Bonadonna (2015), Grain-size features of two large eruptions from Cotopaxi volcano1226(Ecuador) and implications for the calculation of the total grain-size distribution, Bulletin of Volcanology,122777(7), 64, doi:https://doi.org/10.1007/s00445-015-0949-4.
- Vasconez, F., D. Sierra, M. Almeida, D. Andrade, J. M. Marrero, P. A. Mothes, et al. (2017), Mapa preliminar de amenazas potenciales del volcán Cotopaxi—Zona oriental, IG-EPN, Quito, Ecuador.
- Vázquez, R., R. Bonasia, A. Folch, J. L. Arce, & J. L. Macías (2019), Tephra fallout hazard assessment at Tacaná
 volcano (Mexico), *Journal of South American Earth Sciences*, *91*, 253-259,
 doi:https://doi.org/10.1016/j.jsames.2019.02.013.
- Volentik, A. C. M., & B. F. Houghton (2015), Tephra fallout hazards at Quito International Airport (Ecuador),
 Bulletin of Volcanology, 77(6), 50, doi:https://doi.org/10.1007/s00445-015-0923-1.
- Wilson, G., T. M. Wilson, N. I. Deligne, & J. W. Cole (2014), Volcanic hazard impacts to critical infrastructure: A
 review, *Journal of Volcanology and Geothermal Research*, 286, 148-182,
 doi:https://doi.org/10.1016/j.jvolgeores.2014.08.030.
- Wilson, T. M., C. Stewart, V. Sword-Daniels, G. S. Leonard, D. M. Johnston, J. W. Cole, et al. (2012), Volcanic ash
 impacts on critical infrastructure, *Physics and Chemistry of the Earth, Parts A/B/C*, 45, 5-23,
 doi:https://doi.org/10.1016/j.pce.2011.06.006.
- Wolf, T. (1904), Crónica de los fenómenos volcánicos y terremotos en el Ecuador con algunas noticias sobre otros países de la América Central y Meridional desde 1535 hasta 1797, Imprenta de la Universidad Central de Quito, Quito, doi:<u>http://www.dspace.uce.edu.ec/handle/25000/14200</u>.
- Wright, H. M. N., K. V. Cashman, M. Rosi, & R. Cioni (2007), Breadcrust bombs as indicators of Vulcanian
 eruption dynamics at Guagua Pichincha volcano, Ecuador, *Bulletin of Volcanology*, *69*(3), 281-300,
 doi:https://doi.org/10.1007/s00445-006-0073-6.
- Yang, Q., E. B. Pitman, M. I. Bursik, & S. F. Jenkins (2021), Tephra deposit inversion by coupling Tephra2 with the Metropolis-Hastings algorithm: algorithm introduction and demonstration with synthetic datasets, *Journal* of Applied Volcanology, 10(1), 1-24, doi:https://doi.org/10.1186/s13617-020-00101-4.

 Yang, Q., E. B. Pitman, E. T. Spiller, M. I. Bursik, & A. Bevilacqua (2020), Novel statistical emulator construction for volcanic ash transport model Ash3d with physically motivated measures, *Proceedings of the Royal Society A*, 476(2242), 20200161, doi:https://doi.org/10.1098/rspa.2020.0161.

1254 **References from the supporting information**

Tadini, A., O. Roche, P. Samaniego, N. Azzaoui, A. Bevilacqua, A. Guillin, et al. (2021), Eruption type probability
 and eruption source parameters at Cotopaxi and Guagua Pichincha volcanoes (Ecuador) with uncertainty
 quantification, *Bullettin of Volcanology*, *83*(35), doi:https://doi.org/10.1007/s00445-021-01458-z.