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Tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes (Ecuador) with uncertainty quantification

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Key Points:

- We develop tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes using the PLUME-MoM/HYSPLIT model
- We incorporate the quantification of the uncertainty on the input parameters, the model, and the occurrence of different eruption types
- Our study indicates that full uncertainty quantification is essential in volcanic hazard assessment in order to provide robust information

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

32 Abstract

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

53 Plain language summary

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

67 1 Introduction

68 Among the numerous hazards related to volcanic eruptions, tephra fallout is certainly one
69 of the most severe because it may affect large areas ($> 100 \text{ km}^2$; Blong, 1996) and has a dramatic
70 impact on both human settlements and activities (Brown *et al.*, 2017). While tephra residence in
71 the atmosphere can lead to near-total disruption of air traffic over a vast region (e.g.,
72 Eyjafjallajökull 2010 eruption; Budd *et al.*, 2011; Bursik *et al.*, 2009; Folch *et al.*, 2012; Folch &
73 Sulpizio, 2010), tephra accumulation on the ground affects human health (Baxter, 1990; Baxter
74 & Horwell, 2015), buildings stability (Macedonio & Costa, 2012; Spence *et al.*, 2005),

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

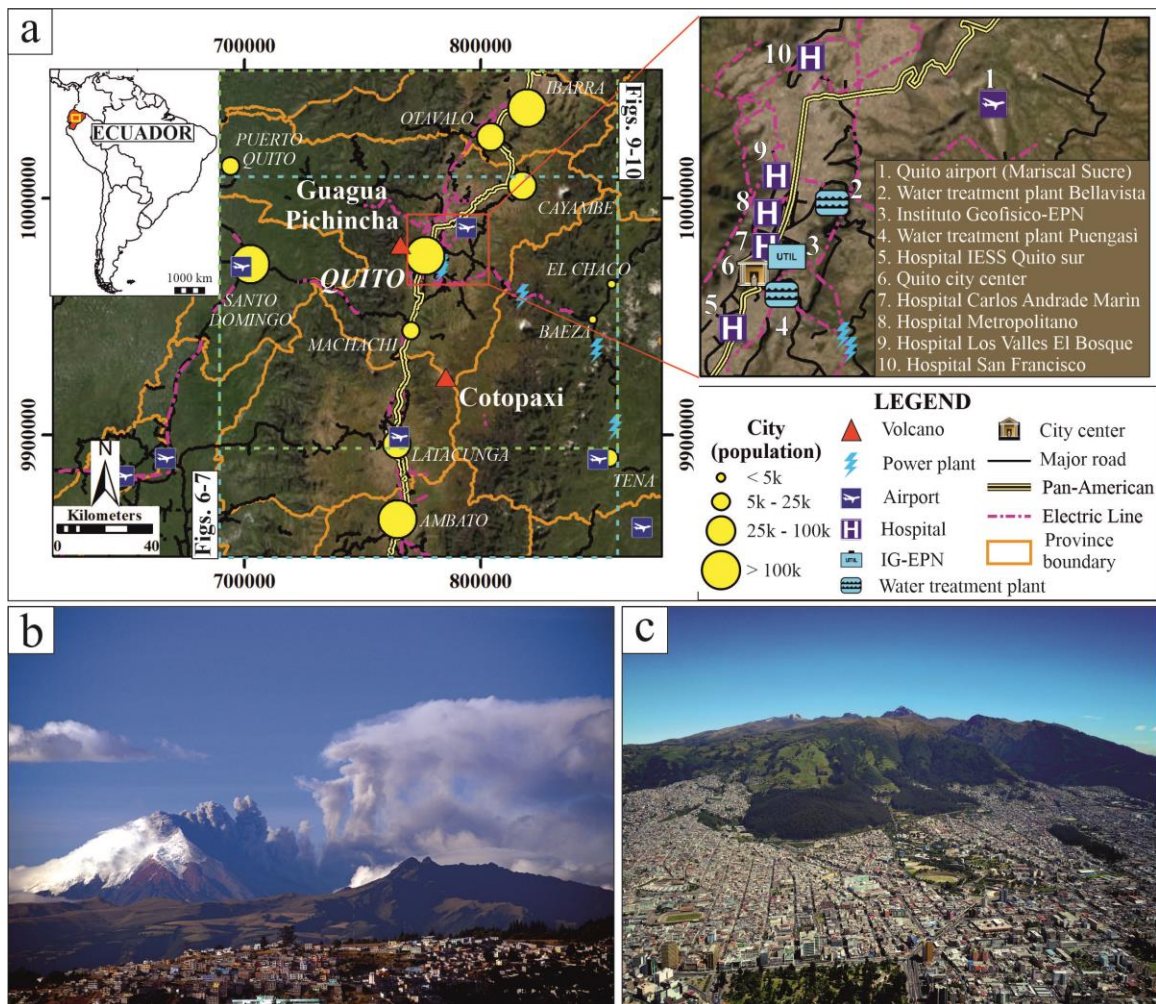
110 This paper presents a tephra fallout hazard assessment study, which focuses on the area
111 of Quito, Ecuador's capital city. In order to perform this study, we focus on Cotopaxi and
112 Guagua Pichincha, which are located nearby the city and are currently active volcanoes with
113 recent eruptions.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

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

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

132 2 Background

133 Quito, Ecuador’s capital city, is located in the inter-andean valley, within the province of
 134 Pichincha (Fig. 1a). With almost three millions of inhabitants it is also the largest city in the
 135 country, it hosts the largest airport in Ecuador and it is in the middle of the most important road
 136 systems (e.g. the “Pan-American highway”; Fig. 1a).



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

146 2.1 Cotopaxi

147 According to Hall & Mothes (2008), the eruptive history of Cotopaxi volcano (Fig. 1a
 148 and b) began about 500 ka and has been firstly characterized by dome-forming to Plinian
 149 eruptions (up to VEI 4-5 or greater), which erupted mostly rhyolitic magmas (70–75 wt.% SiO₂).
 150 In contrast, from ~4 ka until present day, magmas erupted were almost all andesitic in
 151 composition (56–62 wt.% SiO₂). The latter period of activity (i.e. the last 2000 years) with
 152 andesitic magmas include violent Strombolian VEI 2-3 (in the XIX century, Pistolesi *et al.*,
 153 2011), sub-Plinian VEI 3-4 (AD 1877 or XVIII century, Pistolesi *et al.*, 2011) and Plinian VEI 4-
 154 5 (Layer 3/X, 820±80 years BP; Layer 9/5/L-2, 1,180±80 years BP; Barberi *et al.*, 1995; Biass &
 155 Bonadonna, 2011; Hall & Mothes, 2008) eruptions. The last eruption of Cotopaxi is the AD 2015
 156 VEI 1-2 eruption, characterized by an opening hydrovolcanic phase followed by a ~3 months
 157 long ash emission, which erupted a total of ~ 8.6x10⁵ m³ of tephra and caused a severe air traffic
 158 disturbances and impacted rural activities in the region (Bernard *et al.*, 2016; Gaunt *et al.*, 2016;
 159 Hidalgo *et al.*, 2018).

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

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

195 2.2 Guagua Pichincha

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

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

230 been considered with fixed eruptive source parameters, while wind profiles were statistically
231 sampled at each iteration. Resulting maps described the expected tephra thickness (in mm) for
232 given probabilities (1, 25, 50, 75 and 99%).

233 **3 Methods**

234 3.1 Numerical modelling

235 3.1.1 PLUME-MoM/HYSPLIT model

236
237 After its first release (de'Michieli Vitturi *et al.*, 2015), PLUME-MoM has been recently
238 upgraded to a new version (PLUME-MoM-TSM, with "TSM" standing for "two-sized
239 moments"; de' Michieli Vitturi & Pardini, 2021). This model describes the steady-state dynamics
240 of a plume in 3D coordinates through a system of equations for the conservation of mass,
241 momentum, energy, and the variation of heat capacity and mixture gas constant. The model
242 considers radial and crosswind air entrainment, and it adopts the method of moments to describe
243 a continuous size distribution of one or more group of particles (e.g., with different densities,
244 shapefactors,etc.). Moreover, PLUME-MoM-TSM can simulate, for sustained eruptions, the
245 initial spreading of the umbrella cloud due to the development of gravity currents originating
246 from the plume overshoot (i.e. above the neutral buoyancy level). This feature allows a more
247 detailed computation of the spreading of the umbrella cloud, especially in its upwind part. In
248 PLUME-MoM-TSM, the amount of mass released is computed i) along the plume centerline, at
249 emission points located at fixed height; ii) from the area defined by the umbrella cloud. Both the
250 emission points and the umbrella cloud area represent the source locations for HYSPLIT.

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

268 3.1.2 Uncertainty quantification for the numerical model

269 In this paper we apply the procedure for the quantification of the uncertainty of tephra
270 fallout model described in Tadini *et al.* (2020). In the latter, the coupled PLUME-
271 MoM/HYSPLIT model has been used to reproduce four past eruptions from Tungurahua and

272 Cotopaxi volcanoes (in Ecuador) and Puyehue-Cordón Caulle volcano (in Chile). Input
 273 parameters for these eruptions have been collected after a thorough literature review, as well as
 274 from ground deposit and plume height measurements. The uncertainty was quantified by
 275 computing the differences between modeled and observed data of plume height above the vent,
 276 and mass loading and grain size at given stratigraphic sections. Regarding mass loading (kg/m^2)
 277 in particular, for each eruption type and meteorological dataset tested, Tadini *et al.* (2020)
 278 calculated the model mean overestimation (MO) and the mean underestimation (MU),

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

280 where Δ is the difference between the computed and the observed values of mass loading
 281 (in kg/m^2) evaluated for sections with indexes from $i=1$ to, respectively, N_o and N_u . These latter
 282 are the numbers of sections with overestimation and underestimation, respectively. MO and MU
 283 values were divided by the mean value of mass loading measured in the field for all the
 284 considered sections (MML), thus giving two coefficients (MO/MML and MU/MML), which we
 285 will use in section 3.3.1 to account for, respectively, model overestimation and underestimation.
 286 This approach has the advantage of summarizing the errors in two coefficients. However, we
 287 note the average of differences at all the sections may be far from representative of the errors at
 288 the sites with greatest or lowest accumulations. Results of the study of Tadini *et al.* (2020)
 289 highlight that: i) the model tends to have (for larger magnitude eruptions) a higher degree of
 290 overestimation rather than underestimation (i.e. $MO/MML > MU/MML$); ii) sections with
 291 underestimation tend to be both in more proximal and medial/distal locations from the vent,
 292 while sections with overestimation tend to be more concentrated in proximal/medial locations
 293 mostly along the main dispersal axis of the deposit; iii) among the different tested meteorological
 294 datasets, none of them is systematically better than the others in minimizing the differences
 295 between modeled and observed mass loading values. With respect to this latter point, the authors
 296 showed also that the employment of more spatially and temporally refined meteorological
 297 datasets do not always improve the result.

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

$$306 MO/MML = 1.48$$

$$307 MU/MML = -0.49$$

308 These two values are related to the Puyehue-Cordón Caulle 2011 sub-Plinian eruption simulated
 309 using the GDAS meteorological data. As a comparison, the two values from Tadini *et al.* (2020)
 310 are larger ($MO/MML = 3.15$; $MU/MML = -1.03$), highlighting how the features introduced with
 311 the new version of PLUME-MoM have allowed reduction of the uncertainty of the model.
 312

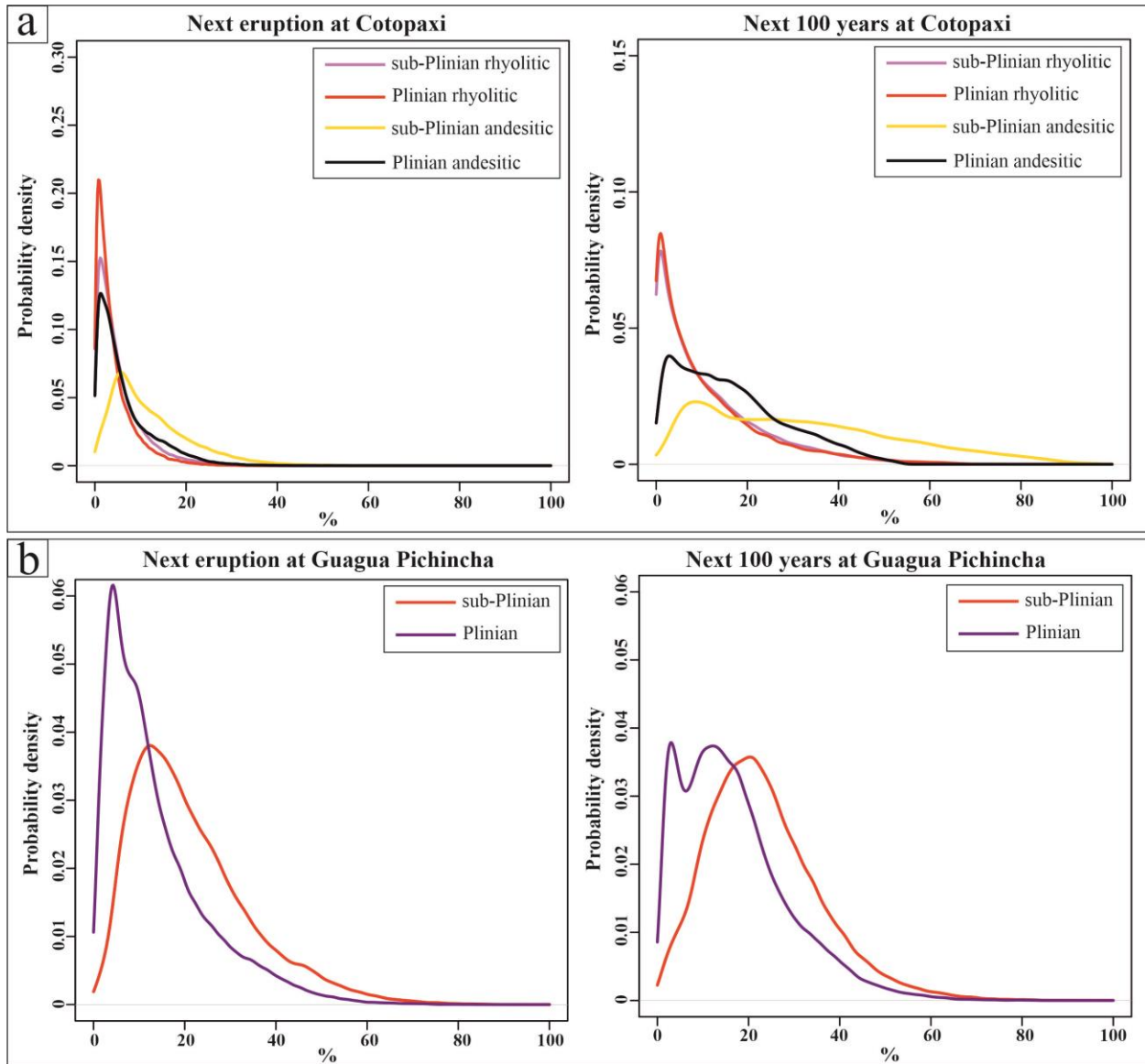
313 3.2 Eruption type probabilities and input parameters for the numerical model

314 3.2.1 Eruption type probabilities

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

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

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



353
 354 **Figure 2.** Uncertainty distributions according to the Classical Model method for the probability
 355 of occurrences of the sub-Plinian and Plinian eruption types for a) Cotopaxi and b) Guagua
 356 Pichincha volcanoes. For both volcanoes the uncertainty distributions are shown for i) the
 357 probability that next eruption will be either sub-Plinian or Plinian (left panels) and ii) the
 358 probability that there will be at least one eruption of each size within the next 100 years
 359 (right panels). y-axis describes the density of the probability density function. Data from Tadini *et al.*
 360 (2021).

361
 362 Mean values of the probability distributions are reported in Table 1, while the three
 363 percentiles for each eruption type are reported in Table S1 from the supporting information. For
 364 Cotopaxi, the graphs of Fig. 2 and the mean probabilities of Table 1 indicate that eruptions
 365 involving rhyolitic magmas are less probable than their andesitic counterparts for the next eruption
 366 but also in the next 100 years time frames. However, the mean probability that the next eruption
 367 will involve a rhyolitic magma is not negligible (10.5% - Table 1). We note that sub-Plinian and
 368 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 (%)
<i>sub-Plinian Rhyolitic</i>	5.9	12
<i>Plinian Rhyolitic</i>	4.6	12
<i>sub-Plinian Andesitic</i>	12	31
<i>Plinian Andesitic</i>	6.9	17
Eruption Guagua Pichincha	Next eruption (%)	Next 100 years (%)
<i>sub-Plinian</i>	22	28
<i>Plinian</i>	14	21

372 **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

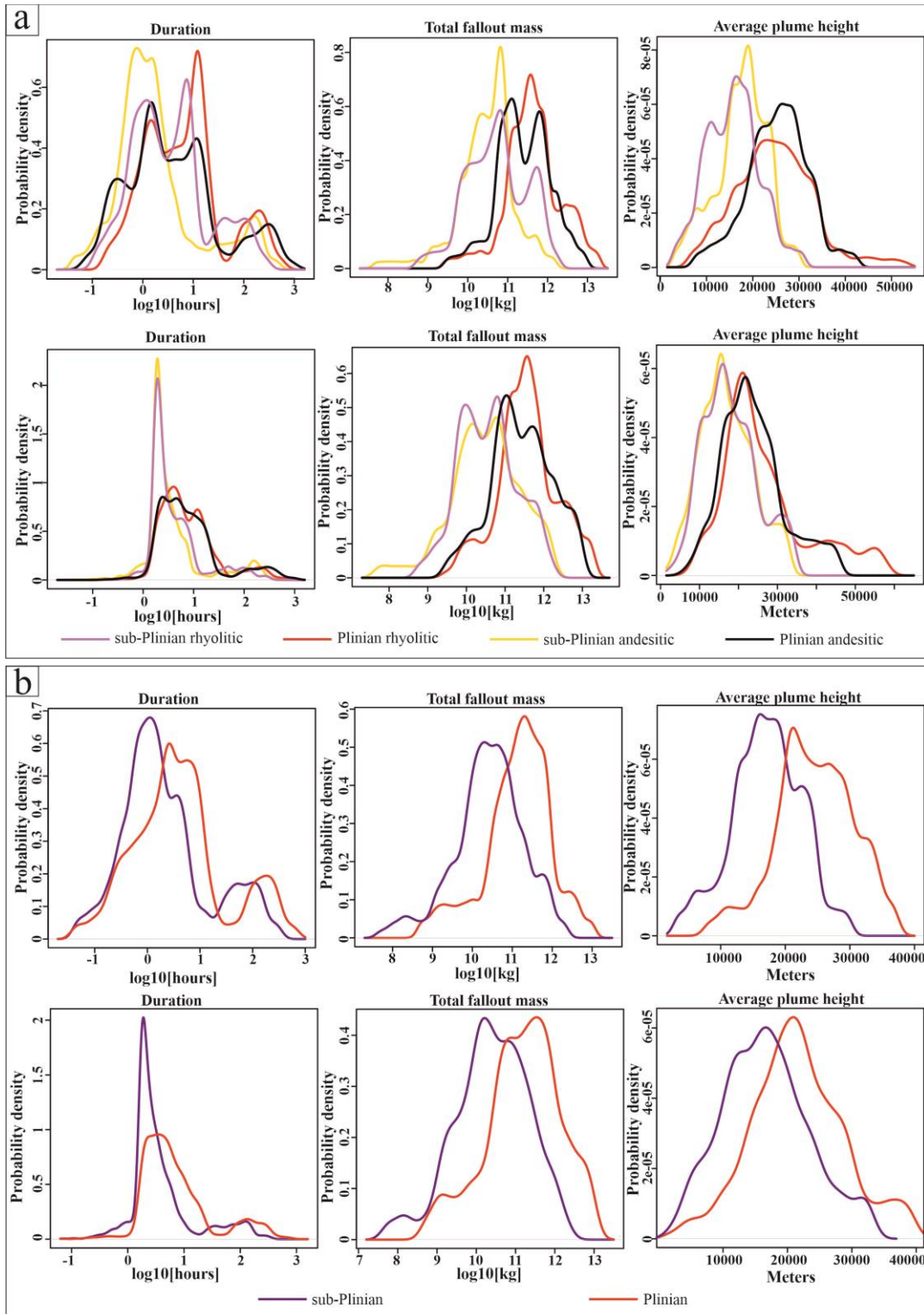
374 We used uncertainty distributions to sample three important parameters for tephra fallout
 375 hazard assessment and numerical modeling, which are eruption duration, total mass of the fallout
 376 deposit, and average plume height. Such distributions were defined by the expert elicitation
 377 session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

381

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

382 **Table 2.** Mean values for duration, total fallout mass and average plume height (Figure 3 and
 383 Tadini *et al.*, 2021) and maximum-minimum values for median (MdΦ) and sorting (σΦ) of the
 384 total grain-size distributions (Costa *et al.*, 2016a). Values in parenthesis are mean values after the
 385 application of the relation of Mastin *et al.* (2009) described in section 3.3.1.

386



387
 388 **Figure 3.** Eruptive source parameters (total eruption duration, total fallout mass and average
 389 plume height), uncertainty distributions according to the Classical Model method (from Tadini *et*
 390 *al.*, 2021; upper panels) and uncertainty distributions recalculated after the application of the
 391 relation of Mastin *et al.* (2009) (eqs. 2 and 3 - lower panels) for a) Cotopaxi and b) Guagua
 392 Pichincha volcanoes. y-axis describes the density of the probability density function.

393

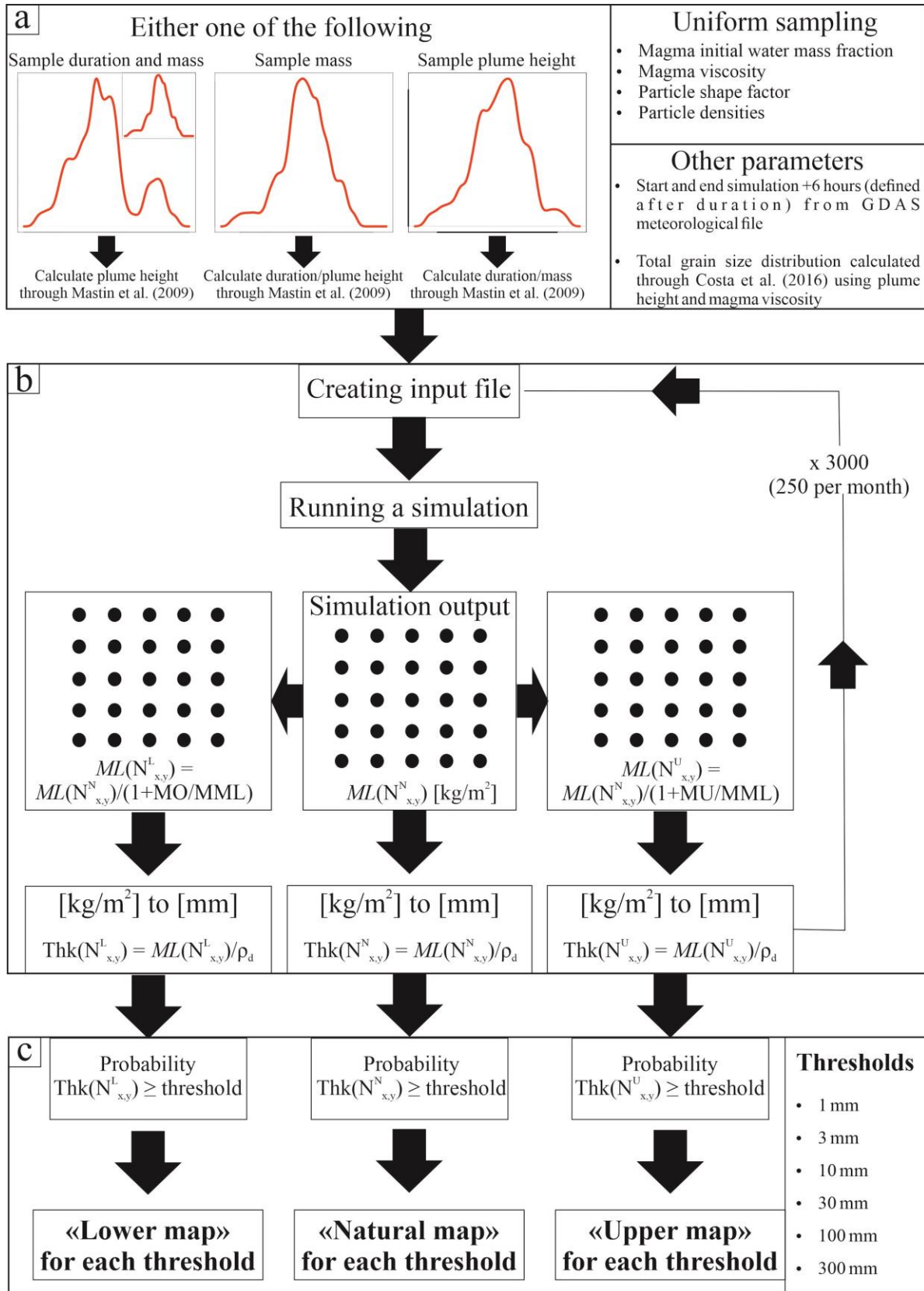
394 For other parameters, such as total grain-size distribution (TGSD), particle densities,
395 particle shape factors (i.e. sphericity), and initial volatile content of magma, we considered an
396 uncertainty range variable between two end members. In detail, for particle density we
397 considered that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

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

429 3.3 Hazard maps and curves

430 3.3.1 Parameters sampling and maps production

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



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

447
 448 The uncertainty affecting the eruptive source parameters (ESPs) was taken into account
 449 with a Monte Carlo sampling (Fig. 4a). The three main ESPs (eruption duration, total mass of
 450 tephra fallout deposit, and average plume height) have been sampled directly from the
 451 distributions provided by Tadini *et al.* (2021) and reported in Fig. 3.

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

$$456 \quad H = 2.00 * VFR^{0.241} \quad (2)$$

$$457 \quad H = 25.9 + 6.64 \log_{10}(V) \quad (3)$$

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

- 461 • total mass is sampled and duration/plume height are calculated (equations 2-3);
- 462 • plume height is sampled and total mass/duration are calculated (equations 2-3);
- 463 • duration and total mass are sampled and plume height is calculated (equation 2).

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

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

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

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

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

511 The uncertainty due to the numerical model has been quantified during the processing of
 512 simulations (Fig. 4b). During this stage, the sampled parameters have been assembled to create
 513 an input file for the model, and at the end of the simulation an output in the form of a sampling
 514 grid has been provided, where each node $N_{x,y}^N$ (with x and y being latitude and longitude
 515 coordinates) has a mass loading value ML (in kg/m^2). By using the two coefficients MO/MML
 516 and MU/MML described in Tadini *et al.* (2020) and in section 3.1.2, two additional maps were
 517 created:

- 518
- 519 • a map with nodes $N_{x,y}^L$ that corrects model overestimation, such that $ML(N_{x,y}^L) =$
 520 $ML(N_{x,y}^N)/(1 + MO/MML)$, where $MO/MML = 1.48$ is the coefficient of
 521 overestimation (see section 3.1.2);
 - 522 • a map with nodes $N_{i,j}^U$ that corrects model underestimation, such that $ML(N_{x,y}^U) =$
 523 $ML(N_{x,y}^N)/(1 + MU/MML)$ where $MU/MML = -0.49$ is the coefficient of
 524 underestimation (see section 3.1.2).

525 The mass loading values of each map (in kg/m^2) were then converted into thickness
 526 values (in mm) by dividing them with deposit density average values. For Cotopaxi we have
 527 used 825 kg/m^3 for andesitic (average among values used by Tsunematsu & Bonadonna, 2015)
 528 and 560 kg/m^3 for rhyolitic (Bonadonna *et al.*, 2015b) magmas. For Guagua Pichincha, given the
 529 general paucity of published data, we have collected 22 samples from tephra fallout deposits
 530 from both the X century (12 samples) and Historic (10 samples) eruption cycles (Figure S3 from
 531 the Supporting Information). The average value of the calculated deposit densities (measured as
 532 the ratio mass/volume of the 22 samples) yields an average value of 745 kg/m^3 .

533 Once all simulations were finished, probabilistic maps were produced in a post-
 534 processing stage (Fig. 4c) following the approach of Bonadonna (2006). According to this latter,
 535 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
 536 determined by summing the number of times a certain thickness threshold (Thk) is reached and
 537 dividing it by the total number m of the simulations:

$$538 \quad P_\tau(N_{x,y}^N) = \frac{\sum_{i=1}^m n_i}{m} \quad (4)$$

539 where

$$540 \quad n_i = \begin{cases} 1, & \text{if } [Thk(N_{x,y}^N) \geq \tau] \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

542

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

548 3.3.2 Maps and curves format

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

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

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

570

571

572 3.3.3 Merging of the maps

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

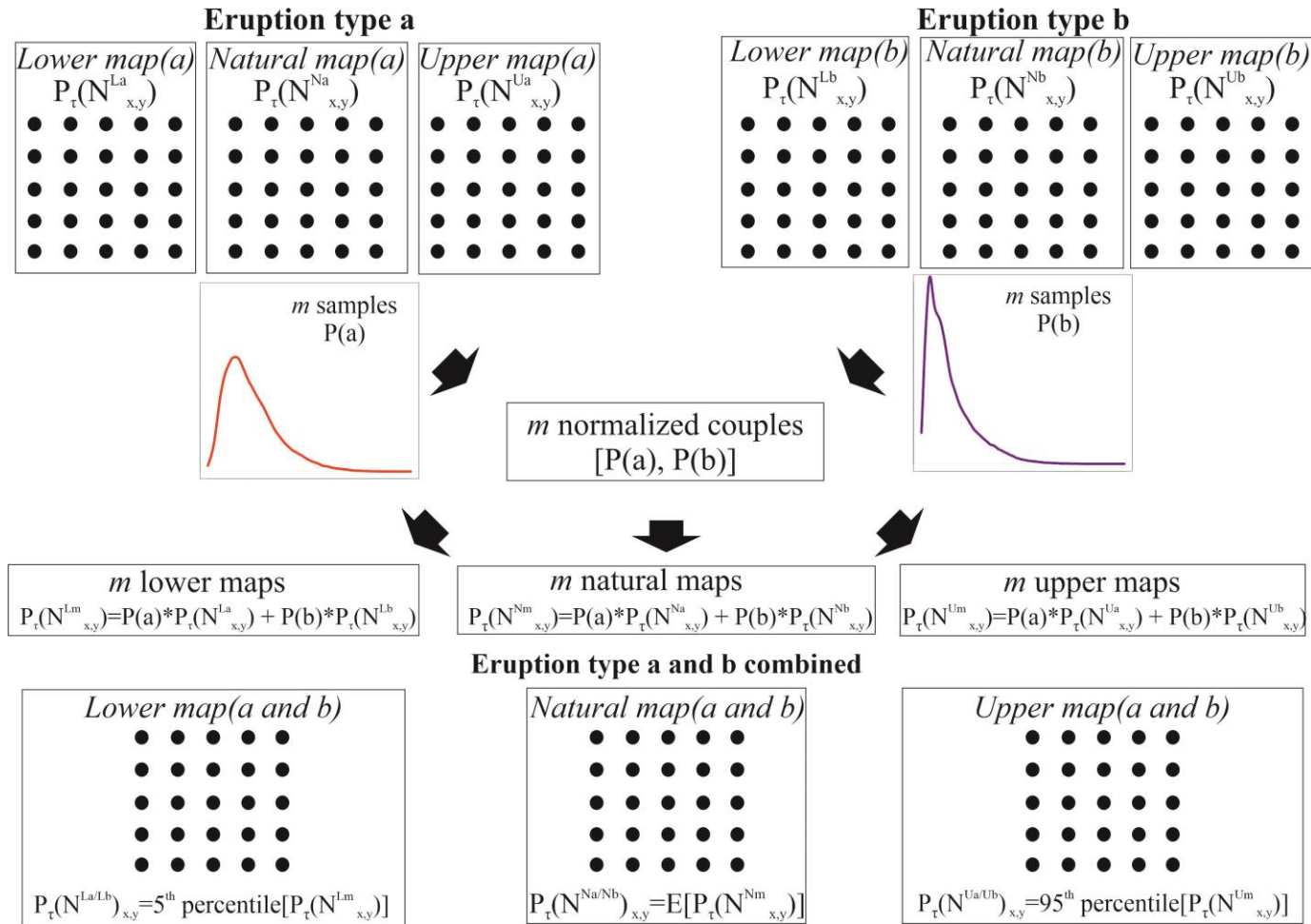
581 In more detail, in case of two eruption types a and b (Fig. 5), for each thickness threshold,
 582 the procedure illustrated in section 3.3.1 provides two sets of three output maps (Lower, Natural
 583 and Upper). Each map is composed of a series of nodes ($N_{x,y}^L$, $N_{x,y}^N$ and $N_{x,y}^U$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

596

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

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

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



608

609 **Figure 5.** Sketch illustrating the procedure used for merging the set of maps of two eruption types (a and b). Two eruption types a and
 610 b have, each of them, a set of three maps (Lower/Natural/Upper). From the distribution of probability of Fig. 2 (next eruption case)
 611 two probabilities (one per distribution) are sampled and then normalized. For each map type, the probability at each node for the
 612 combined a and b is calculated as the weighted mean (using the two normalized values) of the original two maps. This procedure is
 613 performed for $m=1000$ times, yielding (for each node of each map type) a vector of 1000 probability values. Finally, from each vector
 614 is extracted the value corresponding to, respectively, the 5th percentile (for the Lower map) the mean (for the Natural map) and the 95th
 615 percentile (for the Upper map) of the vector.

616 **4 Results and discussion**

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

652 4.1 Cotopaxi

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

659

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

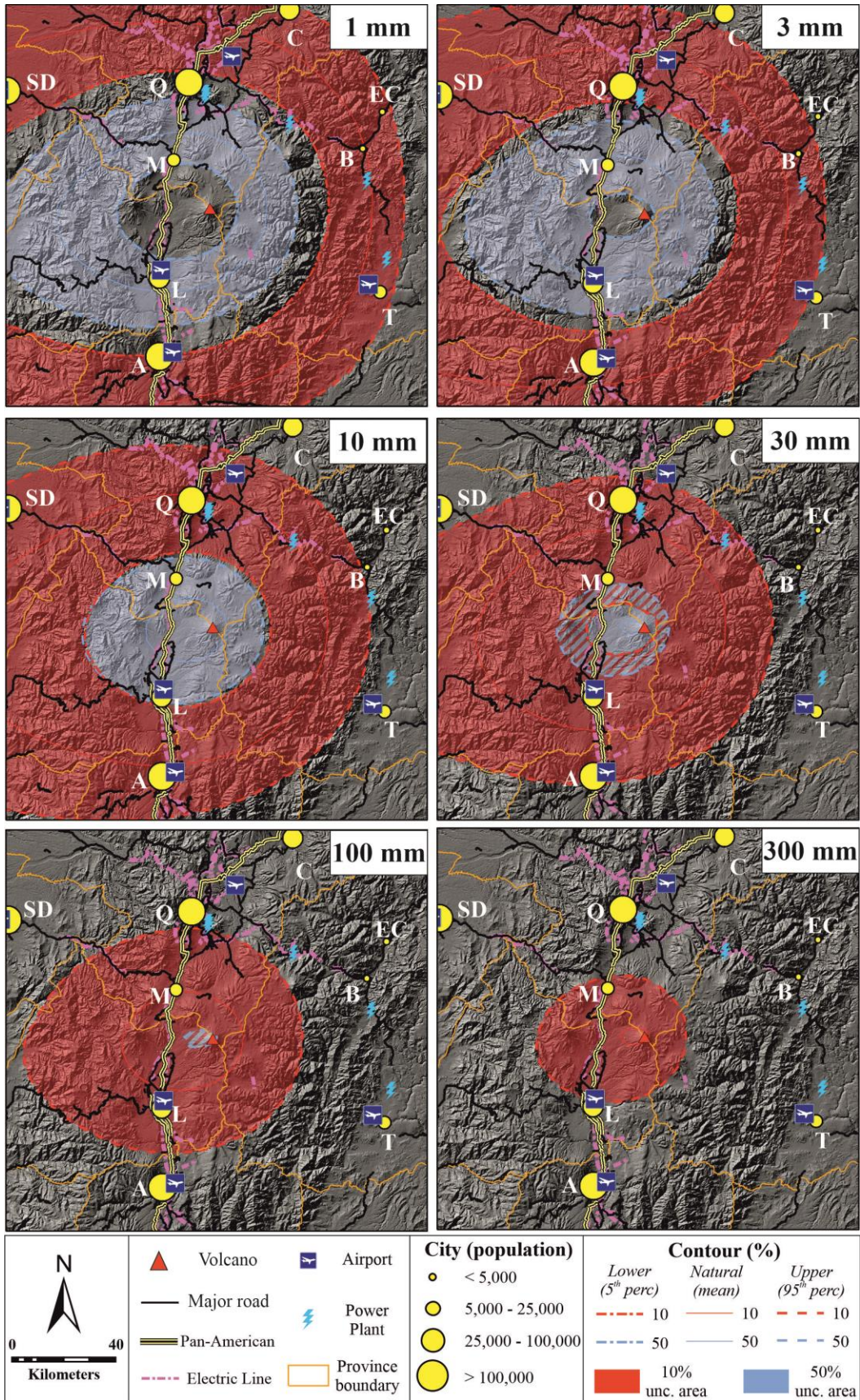
666 Table 3 can be used for a partial comparison with the work of Biass & Bonadonna
667 (2013), with which our paper shares similarities in the modelling strategy and product outputs,
668 although these authors did not consider the uncertainties in the eruption type probabilities and in
669 the numerical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

682 Considering the impact of tephra accumulation on airports, our maps indicate that two to
683 four airports could be affected by a tephra accumulation of 1 mm with a probability of at least
684 10% (see Figs. 6 and 7). Among them, Quito international airport (Fig. 8) could have a tephra
685 accumulation of 1 mm and 10 mm of, respectively, 6-27% and 1-14% (Table S4 from the
686 Supporting Information). Such values are in agreement with those proposed by Volentik &
687 Houghton (2015), who calculated the same probabilities as, respectively, 14-20% and 2.5-6%.

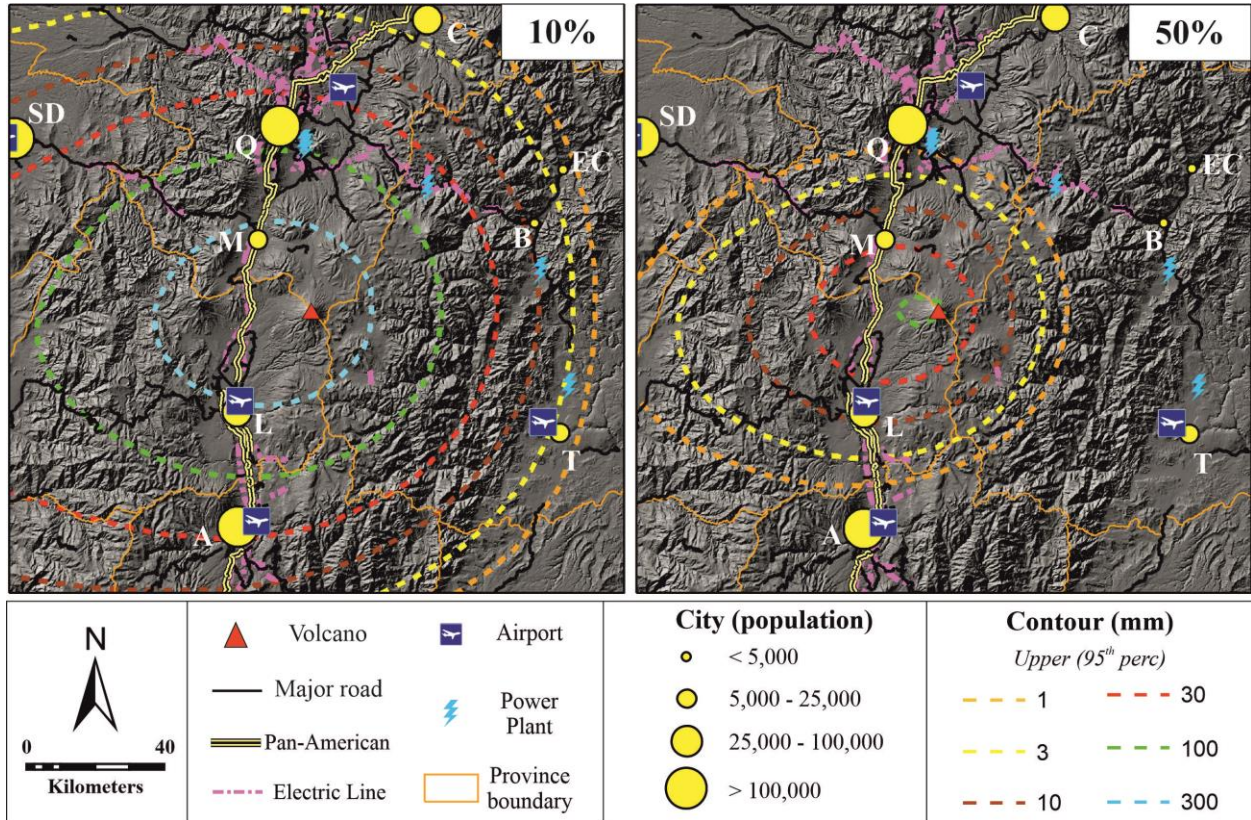
688 Bebbington *et al.* (2008) estimated that an accumulation of 1-2 mm of ash could be
689 sufficient for flashovers to occur along the normal electrical networks, and therefore to cause
690 voltage fluctuations and power shutdown, as also shown by López *et al.* (2016) for Cotopaxi and
691 Tungurahua volcanoes. For Cotopaxi, this accumulation could concern three to five power plants
692 and 329 to 626 km of the electrical network, if we consider, respectively, the lower and upper
693 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).

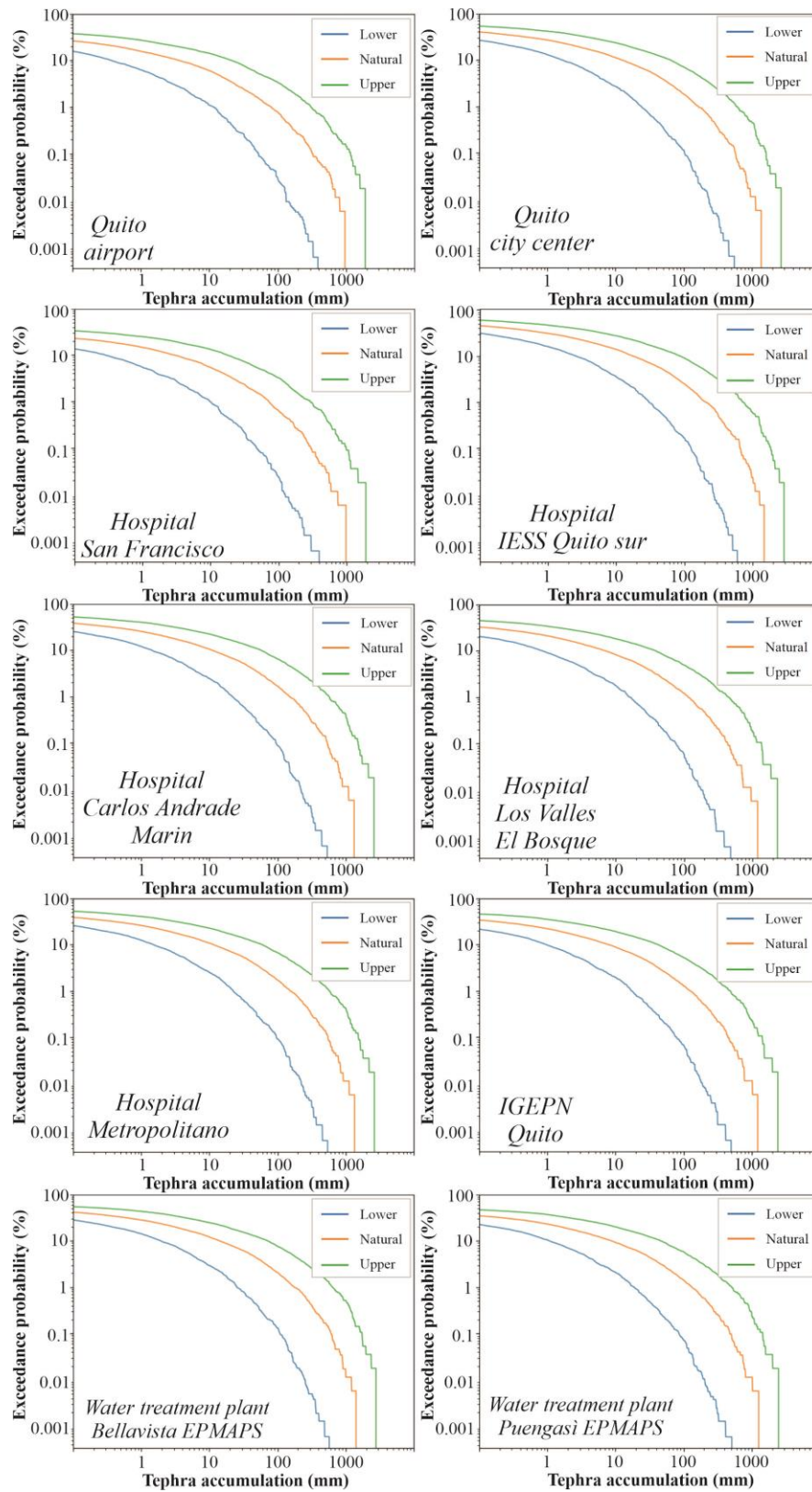
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708 **Figure 6:** Probability maps (Cotopaxi volcano, red triangle) for different thickness
 709 accumulations in case the next eruption is sub-Plinian or Plinian. Uppercase letters are city
 710 names: A = Ambato, T = Tena, L =Latacunga, M = Machachi, B = Baeza, SD =Santo Domingo,
 711 Q =Quito, EC = El Chaco, C = Cayambe. The extent of the maps is the same as the light blue
 712 dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.
 713



714 **Figure 7:** Isopach maps (Cotopaxi volcano, red triangle) for different probabilities in case the
 715 next eruption is sub-Plinian or Plinian. Uppercase letters are city names: A = Ambato, T = Tena,
 716 L =Latacunga, M = Machachi, B = Baeza, SD =Santo Domingo, Q =Quito, EC = El Chaco, C =
 717 Cayambe. The extent of the maps is the same as the light blue dashed box of Fig. 1a. Digital
 718 Elevation Model (30 m- resolution) from Marc Souris, IRD.
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Figure 8. Hazard curves for 10 sensitive sites in Quito in case the next eruption at Cotopaxi is sub-Plinian or Plinian.

Thickness (mm)	Cotopaxi 10% probability Area Covered (km ²)			Cotopaxi 10% probability Population potentially affected		
	Lower (5 th perc)	Natural (Mean)	Upper (95 th perc)	Lower (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 (mm)	Cotopaxi 50% probability Area Covered (km ²)			Cotopaxi 50% probability Population potentially affected		
	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

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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 people potentially affected. For example, for the 30 mm isopach line with 10% probability (Figs. 9-10), the change in the area covered given by the Lower (5th percentile) and Natural (Mean) maps is roughly 4,300 km² (from ~300 to ~4,600 km²; Table 4), but the amount of people potentially involved changes from 425 to more than 2.7 million. Similar effects are evident also 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 the comparison with our results is difficult. However, we note that our maps appear to have 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 toward W (see Figure S1 from the supporting information). This is consequently the main 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 is located) are the major causes for the drastic changes in the population potentially affected. It is

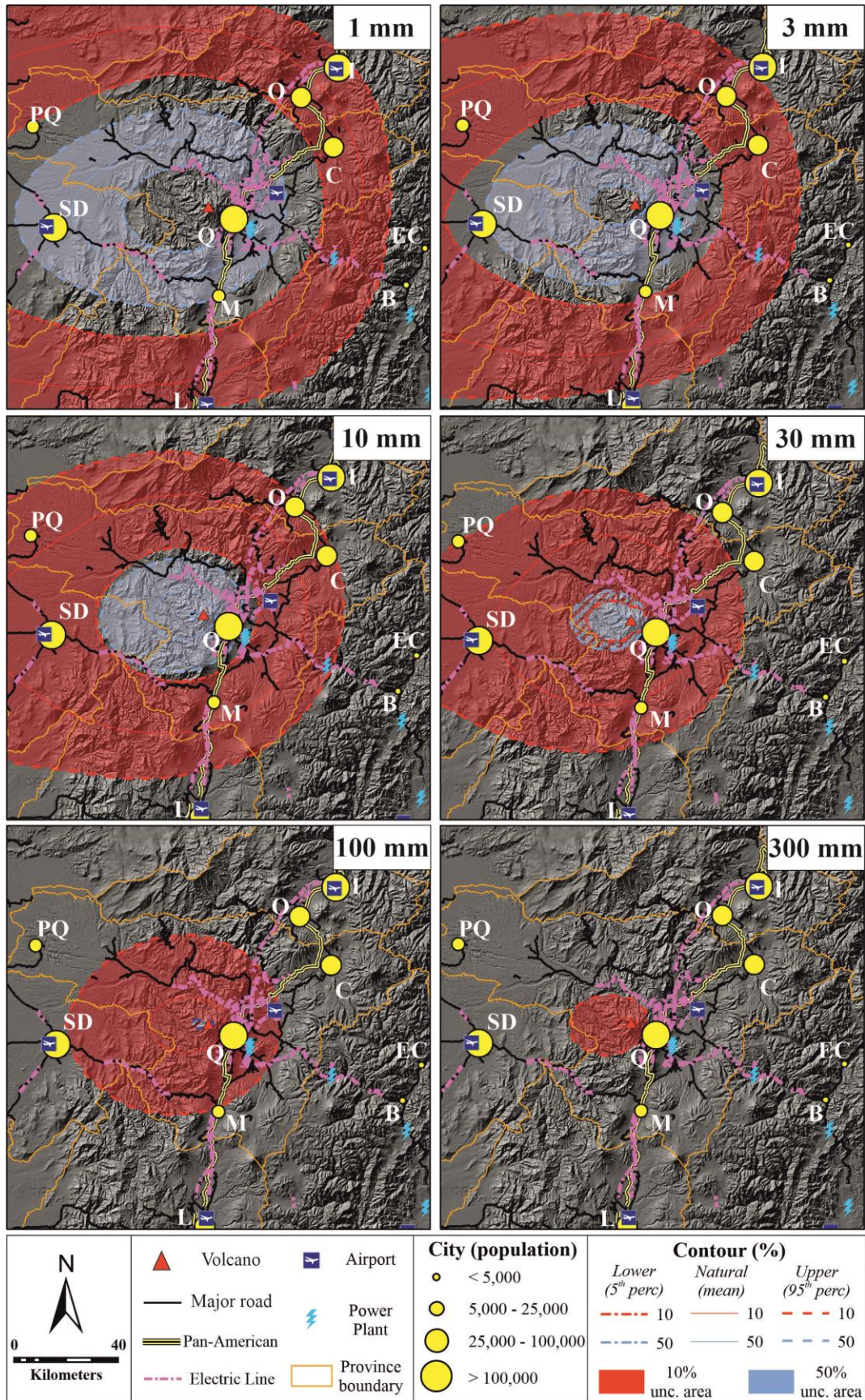
760 however important to highlight that the spatial resolution of the meteorological dataset used
761 plays a role in these situations, since different resolutions could cause fluctuations in the position
762 of the isoline resulting in important variations in the population affected. In this study,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

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

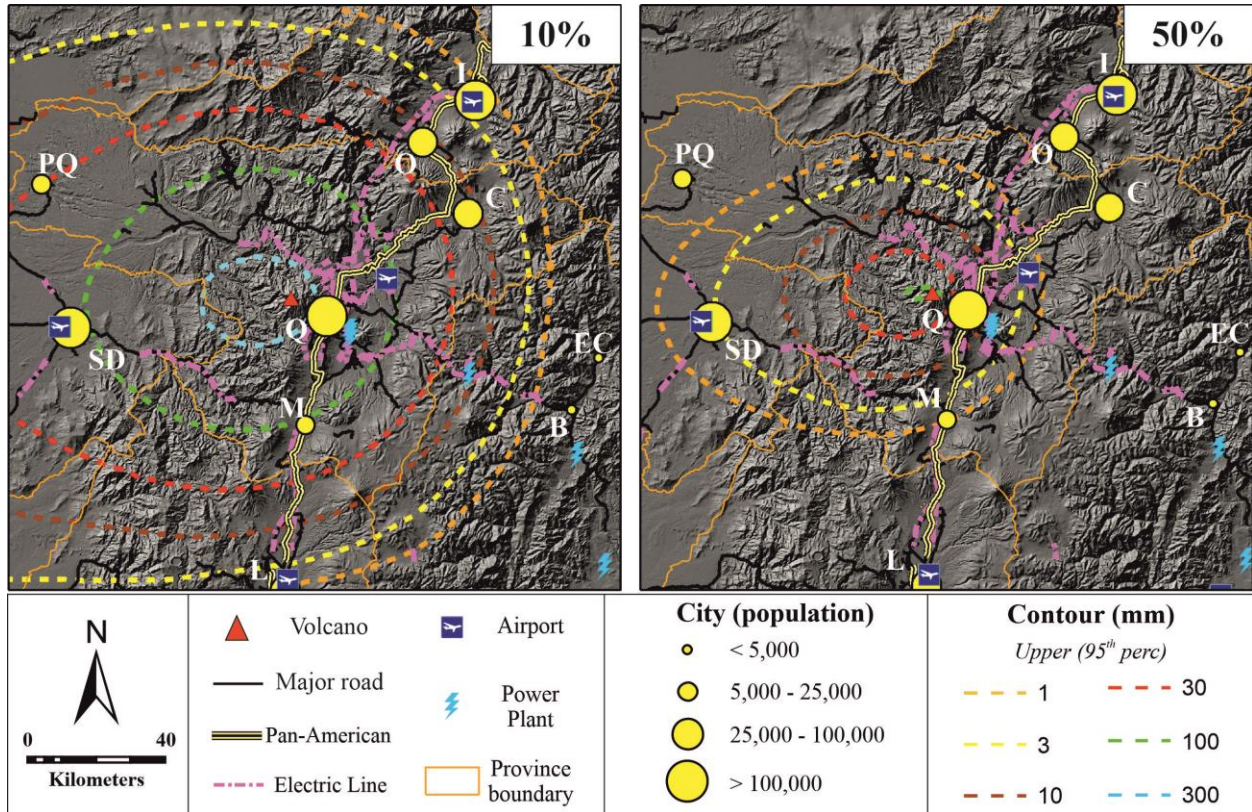
781 Considering the already mentioned threshold of 1-2 mm of ash that could cause electrical
782 flashovers (Bebbington *et al.*, 2008; López *et al.*, 2016) and the maps of Fig. 10, two power
783 plants have 50% probability to have accumulation of 1-3 mm, while another one has 10%
784 probability for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

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

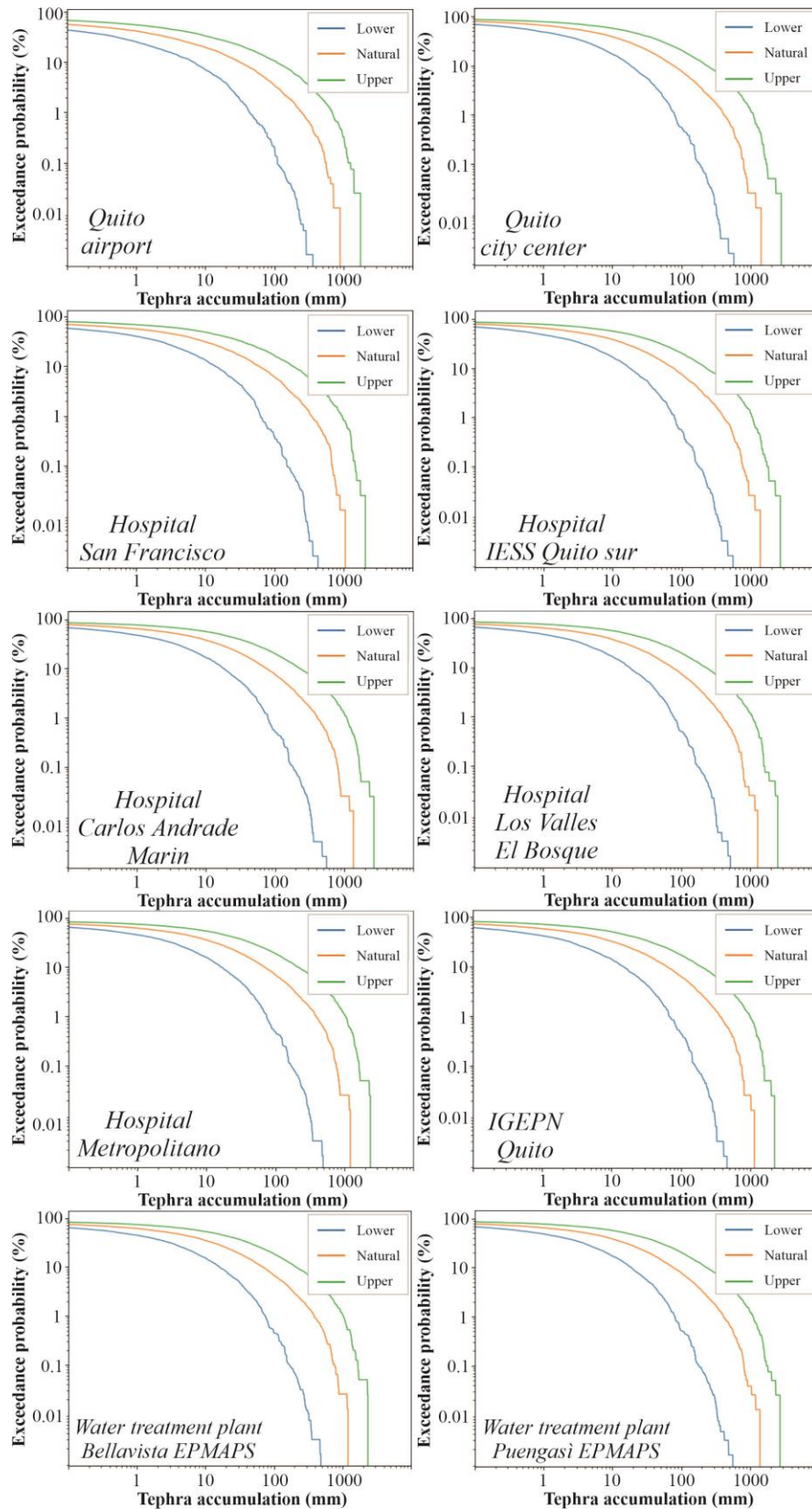
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797 **Figure 9:** Probability maps (Guagua Pichincha volcano, red triangle) for different thickness
 798 accumulations in case the next eruption is sub-Plinian or Plinian. Uppercase letters are city
 799 names: L = Latacunga, M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = El
 800 Chaco, C = Cayambe, PQ = Puerto Quito, O = Otavalo, I = Ibarra. The extent of the maps is the
 801 same as the light green dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from
 802 Marc Souris, IRD.
 803



804 **Figure 10:** Isopach maps (Guagua Pichincha volcano, red triangle) for different probabilities in
 805 case the next eruption is sub-Plinian or Plinian. Uppercase letters are city names: L =Latacunga,
 806 M = Machachi, B = Baeza, SD = Santo Domingo, Q = Quito, EC = El Chaco, C = Cayambe, PQ
 807 = Puerto Quito, O = Otavalo, I = Ibarra. The extent of the maps is the same as the light green
 808 dashed box of Fig. 1a. Digital Elevation Model (30 m- resolution) from Marc Souris, IRD.
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812 **Figure 11.** Hazard curves for 10 sensitive sites in Quito in case the next eruption at Guagua

813 Pichincha is sub-Plinian or Plinian.

Thickness (mm)	Guagua Pichincha 10% probability <i>Area Covered (km²)</i>			Guagua Pichincha 10% probability <i>Population potentially affected</i>		
	<i>Lower (5th perc)</i>	<i>Natural (Mean)</i>	<i>Upper (95th perc)</i>	<i>Lower (5th perc)</i>	<i>Natural (Mean)</i>	<i>Upper (95th perc)</i>
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 (mm)	Guagua Pichincha 50% probability <i>Area Covered (km²)</i>			Guagua Pichincha 50% probability <i>Population potentially affected</i>		
	<i>Lower (5th perc)</i>	<i>Natural (Mean)</i>	<i>Upper (95th perc)</i>	<i>Lower (5th perc)</i>	<i>Natural (Mean)</i>	<i>Upper (95th perc)</i>
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

814 **Table 4.** Area covered and population potentially affected by tephra falls characterized by
815 isopach contours corresponding to 10% and 50% probabilities for next sub-Plinian/Plinian
816 eruption at Guagua Pichincha volcano. Numbers with * indicate that the corresponding isopach
817 extends out of the computational domain, and the number itself is therefore an underestimation.
818

819 5 Conclusions

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

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

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

871 **Appendix: total grain-size distribution**

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

$$874 \quad f_{bi-Gauss}(\Phi) = p \frac{1}{\sigma_1 \sqrt{2\pi}} \exp \left[-\frac{(\Phi - \mu_1)^2}{2\sigma_1^2} \right] + (1 - p) \frac{1}{\sigma_2 \sqrt{2\pi}} \exp \left[-\frac{(\Phi - \mu_2)^2}{2\sigma_2^2} \right] \quad (6)$$

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

881
$$\sigma_1 \approx 0.67 + 0.07 H$$

882
$$\mu_1 + 3\sigma_1 \approx 0.96 + 0.20H$$

883
$$\mu_2 - \mu_1 \approx 1.62(\text{Log}_{10}\eta)^{0.66}$$

884
$$\sigma_2 \approx 1.46$$

885
$$p = 1.61\exp(-0.31\text{Log}_{10}\eta)$$

886 with H the plume height (km) and η the magma dynamic viscosity (Pa s).
 887
 888

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 901 This is Clervolc contribution number XXX.

902 The authors have no competing interests to declare.

903 Data supporting the analyses and conclusions presented in this study could be found in a
 904 repository in the Figshare community with the following DOI:
 905 <https://figshare.com/s/d039d9c741040b70c88c>
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