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

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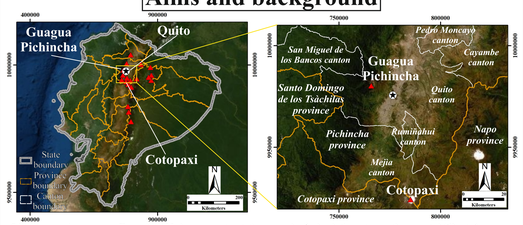
Abstract

Tephra fallout is a major hazard for many human activities, spanning from aviation safety (ash concentration in the air) to building stability (tephra load) as well as health and respiratory problems. Long-term planning is therefore an important task for civil authorities, especially in highly populated areas. Probabilistic hazard maps are useful tools to address these complex issues, and the quantification of the uncertainty associated to such maps represents an equally important element of hazard assessment.

In this work, we present a tephra fallout hazard assessment study related to two volcanoes (Cotopaxi and Guagua Pichincha) directly threatening the capital city of Ecuador, Quito. This work resulted in the production of hazard maps of different formats, in order to meet the needs of both the scientific community and the local authorities. The quantification of the uncertainty was performed in two steps. First, an elicitation session involving 20 experts from different countries and areas of expertise was performed in order to quantify: a) the probabilities of occurrence of different eruptive styles at the two studied volcanoes; b) the range of uncertainty of some key eruptive input parameters (total fallout mass, eruption duration, plume height, total grain size distribution). These latter estimations were used to produce hazard maps with different eruptive scenarios. Second, it was quantified the uncertainty of the model used for the development of the hazard maps (the plume model PLUME-MoM coupled with the tephra dispersal model HYSPLIT) using recent eruptions in the Andean context as test cases. Using a combination of eruptive parameters from such uncertainty quantification,, a coefficient of uncertainty has been derived and applied to the final maps to actually quantify the uncertainty related to the model.

Aims and background



- 21 active volcanoes in Ecuador (Holocene activity), several of which threatenes the capital (Quito)
- Few mm of ash accumulation: dangerous for inhabitants and economic activities of the Inter-Andean valley
- Tephra fall hazard maps *with explicit uncertainty quantification* are still lacking for Cotopaxi and Guagua Pichincha volcanoes

PROJECT AIM

creates tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes

UNCERTAINTY QUANTIFICATION

- **1) of the numerical model employed (PLUME-MoM/ HYSPLIT) when reproducing past recent eruption of different magnitudes from Andean volcanoes**
- **2) of the occurrence of different eruptive style at the studied volcanoes (Elicitation)**
- **3) of the range of variations of key eruptive source parameters to be used as input for the model (Elicitation)**

GUAGUA PICHINCHA

~16 km West of Quito

Young (< 60 ka), lavic edifice capped with a dome complex, affected by at least two large sector collapses

Mostly dacitic in composition

Recurrent plinian and dome-forming activity

At least 3 plinian eruptions during the last 2000 years (AD 70, AD 970 and AD 1660)

Long-lasting (decades) eruptive episodes that include a Plinian paroxysm

Last eruption (Vulcanian) occurred in AD 1999-2001 (new cycle)

COTOPAXI

~60 km South of Quito

Oldest eruptive products are 500 ka BP old; 26 eruptive periods during the last 2000 years (~ 1 event/century)

Eruptions involving both andesitic and rhyolitic magmas

Explosive eruptions: regional tephra dispersal, relatively small-volume scoria-rich PDC, large debris flows due to its glaciar

Last large eruption (SubPlinian) in AD 1877, last small eruption (Hydrovolcanic to Ash emission) in AD 2015

References

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Aspinall. (2006) Structured elicitation of expert judgement for probabilistic hazard and risk assessment in volcanic eruptions
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de' Michieli Vitturi et al. (2015) TUMOLI MoM 1.0: A new integral model of volcanic plumes based on the method of moments
Hidalgo et al. (2015) SO2 degassing at Tungurahua volcano (Ecuador) between 2007 and 2013: Transition from continuous to episodic degassing
Pistolesi et al. (2015) Complex dynamics of small-moderate volcanic events: the example of the 2014 Rocoto Crater Cotopaxi, Ecuador
Stein et al. (2015) NOAA'S HYSPLIT atmospheric transport and dispersion modeling system
Bernard et al. (2016) Relationship between volcanic ash fallouts and seismic tremor: quantitative assessment of the 2013-2015 eruptive period at Cotopaxi volcano, Ecuador
Tadini et al. (submitted) Quantifying the uncertainty of a coupled plume and tephra dispersal model: PLUME-MoM/HYSPLIT applied to Andean volcanoes

Acknowledgments

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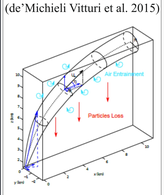
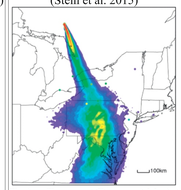
Uncertainty quantification of the numerical model

PLUME-MoM
(de'Michieli Vitturi et al. 2015)



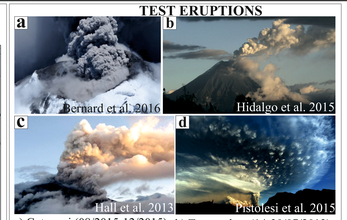
Plume Model
(eulerian steady-state)

HYSPLIT
(Stein et al. 2015)



Tephra Transport/Dispersal Model
(hybrid Eulerian/Lagrangian)

TEST ERUPTIONS



a) Cotopaxi (08/2015-12/2015) Hydrovolcanic/Ash emission
b) Tungurahua (14-30/07/2013) Violent Strombolian
c) Tungurahua (16/08/2006) SubPlinian
d) Cordòn Caulle (04-06/06/2011) SubPlinian

PLUME-MoM/HYSPLIT tested against four eruptions of different magnitudes and styles from three Andean volcanoes, using different meteorological datasets (Tadini et al., submitted)

Uncertainty quantification procedure; differences between modeled and observed data of a) plume height, b) mass loading and c) grain size (Mdφ and σφ).

None of the meteorological datasets tested produced systematically the best results for all the eruptions.

Higher tendency of the model to overestimate observed mass loading (ML) values.

Modeled plume heights: general underestimation with respect to measured data.

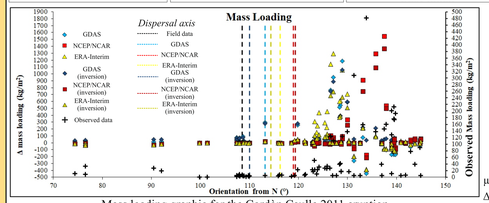
Grain size comparison: important discrepancies between modeled and measured data.

PLUME-MoM/HYSPLIT best suited for studies related to higher magnitude eruptions (i.e. sub-Plinian or Plinian).

The ratios MO/MML and MU/MML are used as coefficients to account for model uncertainty. It is here reported the test case with highest MO/MML and MU/MML ratios, that is the Cordòn Caulle 2011 case

$$MO/MML_{\text{Cordón Caulle 2011}} = 3.15$$

$$MU/MML_{\text{Cordón Caulle 2011}} = -1.03$$



Mass loading graphic for the Cordòn Caulle 2011 eruption
GDAS, NCEP/NCAR, ERA-Interim are simulations done with different meteorological datasets

$$\begin{cases} \dfrac{MO}{MML} = \dfrac{\frac{\sum_{i=1}^{N_O} \Delta_i}{N_O}}{\mu_{ML}} & for\ \Delta_i > 0 \\ \dfrac{MU}{MML} = \dfrac{\frac{\sum_{i=1}^{N_U} \Delta_i}{N_U}}{\mu_{ML}} & for\ \Delta_i < 0 \end{cases}$$

Mean Overestimation (MO)
Mean Underestimation (MU)
Mean Mass Loading (MML)

μ_{ML} = mean of the observed mass loading
Δ mass loading = $ML_{compared}$ - $ML_{observed}$
Δ_i = Δ mass loading for the i-esimal section

Uncertainty quantification of eruptive source parameters and eruption type occurrences

Next eruption at Cotopaxi

SubPlinian rhyolitic	Plinian rhyolitic	Other type rhyolitic	Hydrovolcanic to Ash emission andesitic	Violent Strombolian andesitic	SubPlinian andesitic	Plinian andesitic	Other type andesitic
0.03%	0.02%	0.005%	7.0%	0.8%	0.5%	0.05%	0.05%
4.3%	2.7%	0.8%	56.8%	16.3%	10.4%	4.7%	3.9%
39.0%	36.3%	31.7%	91.7%	66.9%	45.9%	29.2%	39.0%

Structured expert elicitation (Aspinall 2006) involving 20 experts of different backgrounds and expertises

16 seed questions (calibration of experts) and 55 target questions, with the indication (for each question) of the 5th, 50th and 95th percentiles (uncertainty boundaries)

SubPlinian rhyolitic

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
1.30×10^{8}	15	5625
5.28×10^{10}	171	15660
8.19×10^{11}	6312	25100

Plinian rhyolitic

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
9.44×10^{7}	27	10270
4.11×10^{11}	351	24170
7.53×10^{12}	13450	39790

SubPlinian andesitic

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
1.22×10^{8}	9	6627
3.40×10^{10}	75	18060
4.30×10^{11}	9355	25140

Plinian andesitic

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
1.08×10^{10}	11	12940
2.17×10^{11}	177	25530
4.13×10^{12}	19360	34910

Next eruption at Guagua Pichincha

Vulcanian	SubPlinian	Plinian	Other type
13.7%	3.8%	1.1%	0.3%
60.2%	18.5%	10.7%	7.7%
91.3%	58.9%	51.2%	48.9%

Plinian

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
1.62×10^{10}	11	13040
1.65×10^{11}	194	24500
3.55×10^{12}	13590	34230

SubPlinian

Total mass fallout (kg)	Total eruption duration (min)	Average plume height (m)
3.95×10^{8}	9	6864
2.67×10^{10}	88	17150
6.66×10^{11}	6314	25110

Target questions according to the logic trees (each branch is a question) to the left

Two type of questions for each volcano:
1) probability of occurrence of different eruption types for «short-term» perspective (i.e «Probability that the next eruption will be a ... eruption»);
2) range of variation of 3 eruptive source parameters (total mass fallout, total eruption duration and average plume height).

Results analyzed through the Cooke's Classical Method (Cooke 1991); range of variation of the parameters presented here refer to the SubPlinian and Plinian eruption types.

Legend for results to the left:
5th percentile
50th percentile
95th percentile

Range of variations with a triangular distribution fitting the three percentiles. For other input parameters (particle densities, Total Grain Size Distribution, magma initial water content and particle shape factor) it was considered a uniform range of variation between two values.

For Cotopaxi, the probability of occurrence for all the Plinian/Subplinian eruptions considered together (4 cases) for the next eruption is **22.1% (median value).**

For Guagua Pichincha, the probability of occurrence for all the Plinian/Subplinian eruptions considered together (2 cases) for the next eruption is **29.2% (median value).**

Tephra fallout probabilistic hazard maps for Guagua Pichincha and Cotopaxi

Modelling features:
Meteorological dataset employed: GDAS (12/2004-08/2019)
Computational domain 1.5°x1.5°, nodes every 0.05°
MO/MML and MU/MML values (see uncertainty of the model) of the Cordòn Caulle eruption

The maps created are related to SubPlinian and Plinian eruptions considered together:
for Cotopaxi, Plinian/SubPlinian eruptions involving rhyolitic magmas (2 eruption types) and andesitic magmas (2 eruption types)
for Guagua Pichincha, Plinian/SubPlinian eruptions involving dacitic magmas (2 eruption types)

Two type of maps:
1) for a given tephra accumulation threshold (1 mm) and different probabilities. Within each isoline, the probability of exceeding 1 mm is > than the isoline value;
2) for a given probability (10%) and different tephra accumulation thresholds. Within each isoline, there is >10% probability of exceeding the isoline value;

The maps for each volcano (down) have been produced according to the flow chart to the right.

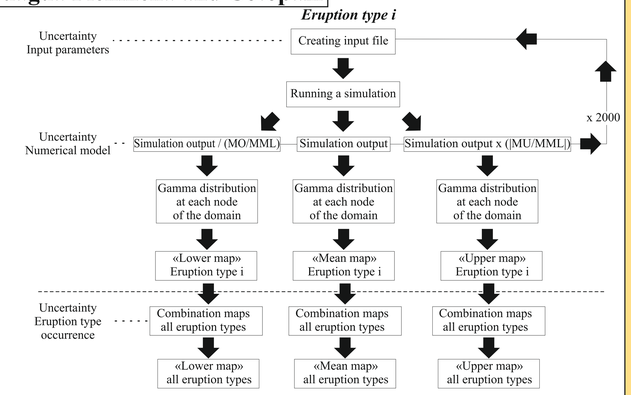
The combination of the maps of all eruption types was based on the following equation:

$$P(x > q) = \int_0^1 \sum_{i=1}^{n} p_i P(x > q \mid T = i) F_i(p_i)$$

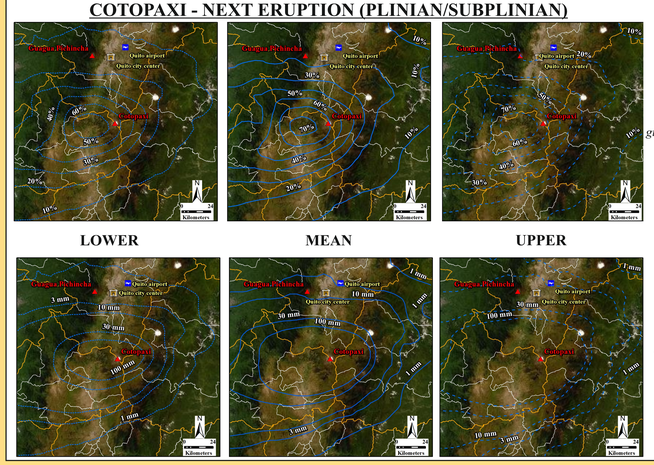
where P(X>q) is the probability of exceedence of the tephra accumulation threshold q, T is the eruption type, p_i is the probability of occurrence of the i-esimal eruption type and F_i is the probability distribution of the i-esimal eruption type (as defined after the elicitation).

The above-mentioned function has been calculated using Monte Carlo approximations based on the elicitated distributions functions.

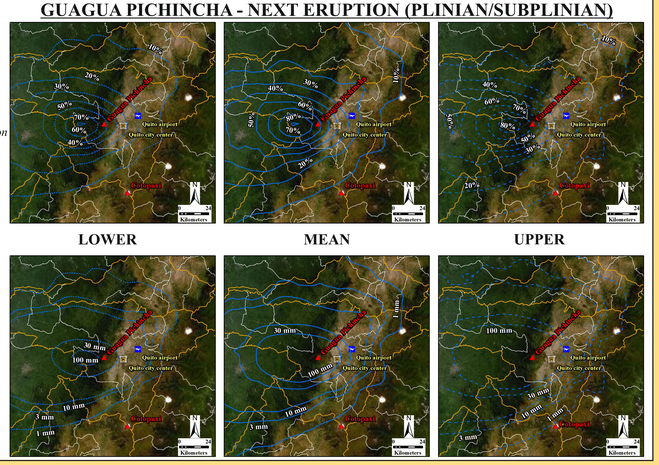
Eruption type i



COTOPAXI - NEXT ERUPTION (PLINIAN/SUBPLINIAN)



GUAGUA PICHINCHA - NEXT ERUPTION (PLINIAN/SUBPLINIAN)



Conclusions

We present a study for developing tephra fallout probabilistic hazard maps for Cotopaxi and Guagua Pichincha volcanoes (Ecuador) with an explicit quantification of epistemic/aleatoric uncertainty at different levels (numerical model, eruption type occurrence and eruptive source parameters).

The uncertainty quantification of the model resulted in the definition of coefficients to account for model mean overestimation/underestimation from the point of view of tephra accumulation.

The uncertainty quantification for both the probability of occurrence of different eruption types and the range of variation of eruptive source parameters was done through an expert elicitation session.

Hazard maps have been produced for the cases of both Plinian and SubPlinian eruption for Cotoapxi (4 eruption types) and Guagua Pichincha (2 eruption types).

Two different types of map have been created:
1) for a given tephra accumulation threshold and different probabilities;
2) for a given probability and different tephra accumulation thresholds.

Each type of map is presented as a set of three maps («lower», «mean» and «upper») which quantify the three main sources of uncertainty.

Future work

Develop other maps for:
1) single eruptions considering a «long-term» perspective (i.e. the next 100 years).
2) different tephra accumulation thresholds (10 mm and 100 mm) and different probability values (e.g. 50%).

Implement hazard curves for sensitive sites in Quito to complete the hazard study.

Investigate other numerical models to find the best-suited ones for the other eruption types not considered here (i.e. Hydrovolcanic/long lasting ash emission, violent strombolian, vulcanian).