Probabilistic hazard assessment of volcanic fallout

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Abstract: This work uses the tephra dispersal model HAZMAP to merge thousands of numerical simulations into probabilistic tephra fallout hazard maps of the Teide volcano in the Canary Islands. Based on historical and meteorological geological data, 7,306 individual scenarios are created to produce these probabilistic hazard maps. These maps give the probability of exceeding a certain threshold value of the ground load and allow us to study how the Teide explosion would affect the Canary archipelago.

I. INTRODUCTION

Explosive volcanic eruptions eject into the atmosphere particles which mix with entrained ambient air to form eruption columns. These particles, commonly referred to as tephra, are categorised according to their diameter d as volcanic bombs ($d \geq 64mm$), lapilli ($2mm \leq d < 64mm$), and volcanic ash ($d < 2mm$) [1]. The largest fragments (volcanic bombs) follow ballistic trajectores and are deposited near the eruptive vent. In contrast, the smallest particles (lapilli and ash) mix in the atmosphere and form volcanic clouds that are dispersed downwind and fall to the ground, where they settle at varying distances from the volcano depending on factors like particle size, emission height, and state of the atmosphere. Tephra particles can remain in the atmosphere for days and even months and can travel very far from the volcano, from tens to thousands of kilometers. For this reason, the impact of volcanic fallout can be local or even continental. Depending on the thickness of the resulting fallout deposit, damage can be caused on buildings and infrastructures (tens of centimeters thick), roads, air traffic and airports (millimeters thick), agriculture, and deterioration of air quality [2].
According to the United States Geological Survey (USGS), there are an estimated 1,350 potentially active volcanoes worldwide [3]. For this reason, it is important to assess fallout hazards and perform an evaluation of the potential impacts. This work makes use of the HAZMAP tephra fallout model to construct long-term tephra hazard maps using the island of Tenerife (Teide volcano) as an example.

II. THE PHYSICS OF TEPHRA TRANSPORT

Tephra transport models predict the atmospheric dispersal and the deposition of tephra based on certain atmospheric parameters (e.g. wind direction and intensity), the characteristics of the eruption (erupted mass, eruption column height), and the characteristics of the ejected particles (e.g. size, density and shape factor). Such models rely on the principle of conservation of particle mass, from which the following advection-diffusion-sedimentation equation derives [e.g. 1]:

$$\frac{\partial C}{\partial t} = -\nabla \cdot (uC) + \nabla \cdot (K\nabla C) + \nabla \cdot (u_s C) + S_0 + S_k, \quad (1)$$

where C is the mass concentration of the particle, $\vec{u} = (u_x, u_y, u_z)$ is the wind speed, K is the turbulent diffusivity tensor, u_s is the sedimentation velocity of the particle, $S_0(x, y, z, t)$ is the source term indicating the amount of mass released per unit time, and $S_k(x, y, z, t)$ is the sink term. In order, the terms on the right-hand side of equation (1) correspond to advection of particles by wind, turbulent diffusion of particles, and particle sedimentation. This equation needs to be solved numerically. However, under certain simplifying hypotheses, an analytical solution exists.

III. METHODOLOGY

A. THE HAZMAP MODEL

HAZMAP is a FORTRAN90 code that solves equation (1) analytically by assuming certain approximations [4]:

1. Steady state (no time dependency).
2. The turbulent diffusivity tensor K is considered as a constant in the horizontal and negligible in the vertical.
3. No chemical reactions, *i.e.* no sink term S_k.
4. Constant and homogeneous horizontal wind field and negligible vertical advection, i.e. $\vec{u} = (u_x, u_y)$
5. Particles are assumed to fall vertically and immediately reach the terminal velocity u_s:

$$u_s = \sqrt{\frac{4g(\rho_p - \rho_a)d}{3C_d\rho_a}}, \quad (2)$$

where g is the gravity, ρ_p is the density of the particle, ρ_a is the air density, C_d is the drag coefficient and d

is the diameter of the particle. Since the particles may or may not be spherical, HAZMAP considers empirical adjustments that allow obtaining the C_d value (see APPENDIX). In this way, the particle settling velocity is obtained as a function of its size (d diameter of the particle and ρ_p density) and the viscosity of the air.

Under these approximate conditions, equation (1) is simplified and can be rewritten as:

$$u_x \frac{\partial C_j}{\partial x} + u_y \frac{\partial C_j}{\partial y} - \frac{\partial (u_{sj} C_j)}{\partial z} = K(\frac{\partial^2 C_j}{\partial x^2} + \frac{\partial^2 C_j}{\partial y^2}) + S_0, \tag{3}$$

where C_j is the concentration of the particle class j having a settling velocity u_{sj}. It is also assumed that the wind and diffusion parameters do not change with time. In this way, a semi-analytical solution for ash deposition is obtained for each given wind and eruption characteristics [5].

B. PROBABILISTIC HAZARD ASSESSMENT

Models like HAZMAP can be used to simulate the fallout deposit given an eruption and wind conditions. However, in the case of long-term hazard assessment, large uncertainties exist on how the next eruption will be. Moreover, the exact dates (i.e. the wind conditions) of the next eruption are not known. This uncertainty is typically circumvented by means of a probabilistic approach, i.e. by combining hundreds/thousands of possible wind/eruption scenarios and weighting them according to their probability of occurrence. Each scenario implies one execution of the model for a given wind and eruption conditions.

SOURCE TERM:

The first data needed to solve equation (3) are the erupted mass and the height of the eruption column, which define the source term S_0. In hazard assessment, these external data are obtained from geological field studies of past tephra deposits which are associated with an approximate year and a Volcanic Explosivity Index (VEI) [6]. Each discrete VEI (ranging form 1 to 7, see Table 1) is associated with a range of possible eruption column heights. Since the relationship between VEI and the height of the column is not unique (a range is associated rather than a single value), heights with different VEIs may be superimposed (which should be considered when creating individual scenarios).

In the probabilistic hazard approach, the source term is represented with a Probability Density Function (PDF) that gives the relative probability of a certain column height of ejected material. The first step in the hazard assessment is therefore to construct the PDF of the volcano under consideration (Teide in our case) as follows:

1. A sample of 1000 compatible random column heights is created for each VEI range using the Latin Hypercube Sampling (LHS) random sampling method to minimize this VEI -height uncertainty [7].

2. A PDF is created showing the global behavior of the discrete data to minimize the effect caused by the overlap of heights in the same interval for different VEIs. Where there is overlap, there are more events.

3. The PDF function that best-fits the data is selected.

TABLE I: Relation between eruption column height CH (km), VEI and range of erupted volume [6].

VEI	**CH** (km)	**Volume** (m^3)
0	< 0.1	10^4
1	$0.1 - 1$	10^4
2	$1 - 5$	10^6
3	$5 - 15$	10^7
4	> 10	10^8
5	> 15	10^9
6	> 20	10^{10}
7	> 20	10^{11}

WINDS:

The second input used by the HAZMAP dispersion model is the vertical wind profiles (wind speed and direction) over the volcanic vent. As explained, HAZMAP considers these winds to be steady and uniform along the horizontal. We consider data for the different scenarios from the ERA-5 reanalysis [8], which provides hourly values for various atmospheric, land, and ocean variables. ERA-5 data covers the Earth in a square grid with a resolution of 0.25° . Since the volcano may or may not be located directly in one of the nodes, wind profiles are obtained at four points in the vicinity, as well as the corresponding vertical values (37 pressure levels measured in mb). A wind profile is randomly assigned to each eruption scenario (the underlying assumption is that the future winds will statistically be the same in the future than in the past and that the PDF will not vary with time).

C. SCENARIOS

Using the values of the wind profiles and the volcano PDF, equation (3) is solved for each scenario (each scenario consists of data from a randomly assigned wind profile and source term). A set of winds was discharged and the probability that an eruption was associated with a certain height was created. Using this data, the number of winds corresponding to each height is calculated and randomly assigned. For example, if there is a 15% probability that an eruption is 1 km high and we have 200 winds; 30 winds will be randomly assigned to a height of 1 km. In this way, all eruption scenarios are created, characterized by certain parameters: height of the eruption column, wind profile and mass of the eruption.

D. HAZARD MAPS

Once we have created all possible scenarios, these results are combined to create the volcanic hazard map. Each map represents the probability distribution for reaching or exceeding a given tephra deposit thickness.

IV. TEIDE VOLCANO HAZARD MAP

The Teide volcano (3717 m a.s.l.) lies above the central geological structure of Tenerife island, a large collapse caldera measuring 17 km in diameter [9]. Teide started to grow around 0.6My ago and poses a substantial tephra hazard to the whole island. In order to create the Teide volcano hazard map we will follow the steps mentioned above so we will need:

1. The PDF for the source term, S_0, inferred from the past eruptive behaviour.
2. Climatically representative direction and velocity of winds above the vent.

A. HISTORICAL EVENTS - PDF

The first step in the hazard assessment process is to obtain field-based data from the geological eruptive record in order to characterize and quantify the past volcano activity. The Smithsonian Institution's Global Volcanism Project maintains a database of the dates and Volcanic Explosivity Index (VEI) of Earth's active volcanoes and their eruptions from the Holocene, covering roughly the last 10,000 years (Program of Global Volcanism, 2013). In addition, further data has been added from [10], which focuses exclusively on the collection of data from Teide volcano. In both cases, the connection between the VEI and eruption volume is obtained from tabulated values (USGS) (Table 1). A Probability Density Function (PDF), giving the probability of the next eruption reaching a given column height, was created based on data from 21 past Teide events recorded in these sources. This process consists of the analysis of the activity data and a statistical approach to obtain the repetitions of the column height by fitting Pearson, Gamma, and normal (Gaussian) distributions. Figure 1 shows the best-fit distribution (the Gamma function) obtained by using the mean square error as the best-fit metric. In our case, the absolute PDFs give the probability distribution of the column height assuming that the eruption occurred, so the probability of having an eruption with any column height is 1.

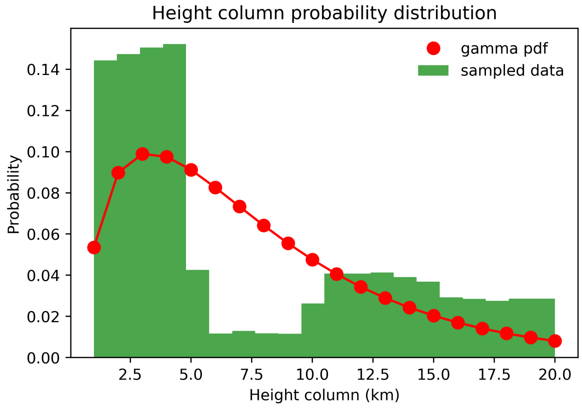

FIG. 1: Column height PDF for Teide volcano.

As observed, most likely future events are associated with column heights of less than 5 km.

B. WINDS

The HAZMAP model simulations use vertical wind profiles above the vent to advect volcanic ash and determine ground deposits. In addition, this model considers winds as steady and homogeneous in the horizontal (i.e. with z dependence only). The process to retrieve ERA5 reanalysis data for the considered period makes use of a Python script that extracts and converts 4-times daily ERA5 NetCDF files into HAZAMP input files containing the wind profiles above Teide every 12-hours for the period 2012-2022 (10 years). The total number of profiles is therefore 7306, each driving a possible HAZAMP wind scenario.

C. SAMPLE EVENTS

With the 7306 wind profiles and the column height data (PDF), the eruption scenarios can be created, each characterized by a specific set of eruption source parameters and a fixed wind profile. This is done by sampling using the Latin Hypercube Sampling (LHS), a technique that produces a statistically valid data set much more efficiently than a Montecarlo sampling [11]. Each HAZAMP scenario simulates the resulting fallout deposit thickness or load (ground deposited material in kg/m^2).

To this purpose, each column height was obtained separately and the number of samples was determined by the association between column height and recurrence versus the total profile (predefined in 7306). Figure 2 shows the sampled events for the Teide volcano, where each sample is a combination of mass and column height ready to be simulated.

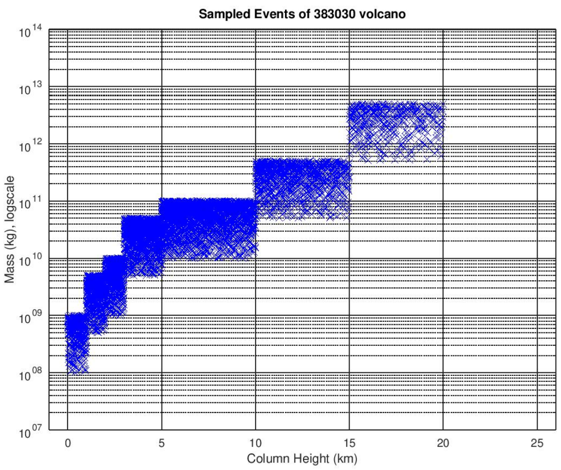

FIG. 2: Sampled events (scenarios) for Teide volcano. Each point represent a HAZMAP simulation.

D. HAZARD MAP

Finally, hazard maps give the probability of exceeding a given threshold value of the ground load. In this case of study, the selected thresholds were 1, 10 and 100 kg/m^2 (these are the most significant in terms of tephra stacking effects), roughly corresponding to deposit thicknesses of 1 mm, 1 cm and 10 cm. The following figures show the obtained results.

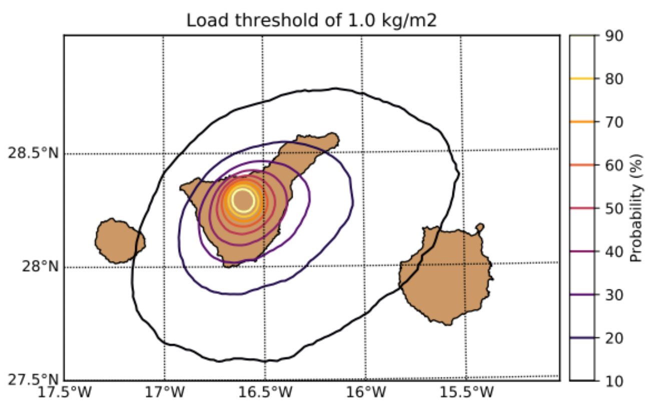

FIG. 3: Hazard map with threshold of 1mm

Figure 3 shows the probability contours for 1 mm thick deposit. At this thickness, infrastructures such as airports are already affected. In the case of a Teide eruption, the two airports of Tenerife (North and South) would be affected with a probability of 20%, i.e, there would be a probability of 20% that the airports would have to be closed, which are often the most effective way of evacuation in Tenerife. Specifically, Tenerife South Airport would have a 40% chance of being closed.

Figure 4 shows the probability contours for 10 cm thick deposit, reflecting that only the areas closest to the volcano would actually have a 40% chance of accumulating 10 cm of volcanic ash (*i.e.* with potential damage to buildings).

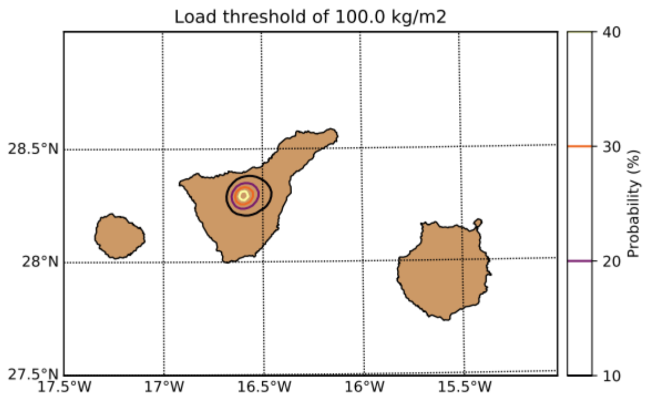

FIG. 4: Hazard map with threshold of 10cm

On the other hand, the ash thickness that would result with a 5%, 50%, and 95% probability is shown in Figures 5, 6 and 7 respectively.

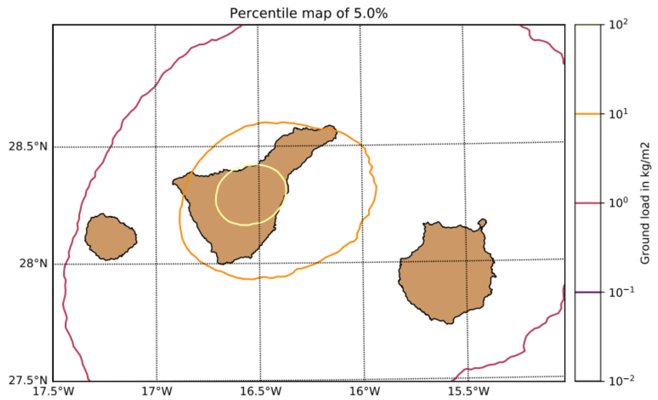

FIG. 5: Percentile map of 5%. Contours show ground load for the 5% worst cases.

Figure 5 shows the 5% probability of reaching an ash loading corresponding to a thickness of 1 mm, 1 cm and 10 cm. The 5% probability of reaching 1 mm covers the islands of Gran Canaria, La Gomera and Tenerife. The probability to reach a 1 cm thickness of ash ir relatively low and the affected area is basically in the proximity of the volcano. With this thickness, some maintenance would be required on supply networks.

Figure 6 shows the 50% percentile (median) for contour thickness of 0,1 mm, 1 mm, 1 cm and 10 cm and, as observed, the affected area is already much smaller. This map shows that the South of Tenerife has more probability of being impacted than the north by a future eruption. Finally, Figure 7 shows the small area that would be affected with a probability of 95%.

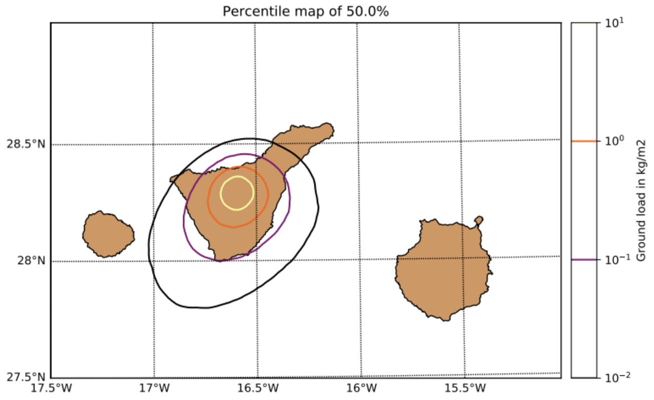

FIG. 6: Percentile map of 50% (median of all scenarios).

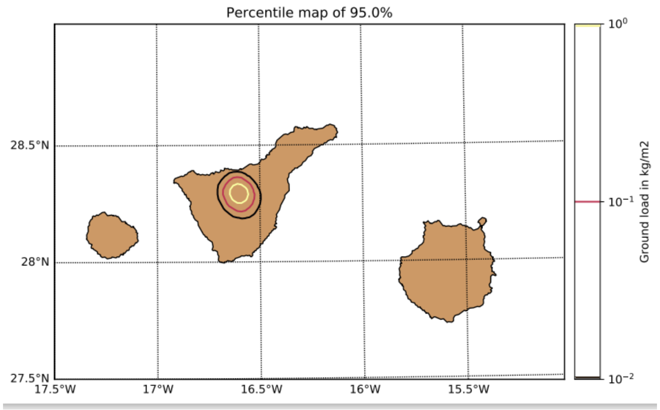

FIG. 7: Percentile map of 95%

V. CONCLUSIONS

1. Hazard maps were obtained merging a total of 7,306 scenarios, a sample large enough to probabilistically represent a future eruptive event.

2. These maps show the impact of different thicknesses of ash and which areas of the island would be most affected, such as the airports that would have to close with a probability of 20% if an eruption of Teide occurred between $0-4$ VEI.

3. The approximations made (*e.g.* steady and homogeneous winds) are necessary to obtain an analytical approximation, and they are good approximations for Teide volcano, since its eruptions do not exceed a VEI of 4. On the other hand, the model implicitly assumes that eruptions are not long-lasting and distances are not very large, otherwise these approximations would no longer be valid.

4. For the understanding of equations (1) and (3), on which this work is based, it helped me to remember the curriculum of the subject "Medis Continus", although it is true, in a more detailed work one could deepen this aspect.

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VI. APPENDIX

DRAGG COEFFICIENT:

For non spherical particles the C_d value is not obvious to calculate. C_d depends on the Reynolds number $Re = dv_s/\nu_a$ where ν_a is the kinematic viscosity of air. We need some definitions to understand what HAZMAP needs to estimate settling velocity:

1. WILSON model [12] using the following interpolation:

$$C_d = \begin{cases} \frac{24}{Re}\varphi^{-0.828} + 2\sqrt{1.07-\varphi} & Re \leq 10^2 \\ 1 - \frac{1-C_d|_{Re=10^2}}{900}(10^3 - Re) & 10^2 < Re \leq 10^3 \\ 1 & Re > 10^3 \end{cases}$$

where $\varphi = (b+c)/2a$ is the particle aspect ratio ($a \geq b \geq c$ denote the particle semi-axes).

2. DELLINO model [13]:

$$v_s = 1.2605\frac{\nu_a}{d}(Ar\xi^{1.6})^{0.5206}$$

where $Ar = d^3(\rho_p - \rho_a)\rho_a/\mu_a^2$

The primary particle shape factor for HAZMAP is the sphericity ψ so it calculates φ and ξ in approximating particles as prolate ellipsoids.