



1. Motivation

- Volcanic hazard assessment is the scientific pillar underpinning the awareness of future eruptive events and the mitigation of their impacts on people, society and the environment.
- Physics-based **Probabilistic Volcanic Tephra Hazard Assessment** (PVTHA) consistently integrates through modelling uncertainties from Eruption Source Parameters (ESPs) and atmospheric conditions that drive tephra dispersal and fallout during eruptions.
- The standard PVTHA workflow presents an important caveat (Figure 1): the sampling of eruption scenarios by means of **Probability Density Functions** (PDFs) typically occurs upstream of the modelling component. As a result, new sets of simulations are required in order to update the downstream hazard mapping whenever PDFs change in time (e.g. during unrest episodes, volcano database updates, etc).

Figure 1. Conceptual comparison between a classical PVTHA computational workflow (a) and the workflow strategy adopted in the ETHM (b). The red boxes indicate the workflow steps that run on High-Performance Computing (HPC) premises and separate the HPC upstream and the HPC downstream workflow steps.

Can hazard maps be updated without re-running the underlying scenarios?

- Idea: sample over a "full-range" of scenarios to create (and store) a massive collection of footprints.
- A **footprint** is a single model realisation together with associated metadata.

2. Characteristics of the ETHM

- User-oriented:** users can furnish PDFs to build customised mappings from a vast catalog of footprints and by means of a lightweight map-creation service. Footprints for 12 European volcanoes were generated running the **FALL3D model** over 30 years of ERA-5 re-analysis data (from 1995 to 2024).
- Single and multi-volcano hazard mapping** by blending contributions from several volcanoes in a selected region (e.g. Italy) or across the whole continent.
- Long and short-term** time scales and filtering of footprints by season or sets of months.
- Multi-scale:** close-range tephra fallout mapping and far-range ash cloud dispersal mapping at relevant atmospheric levels, ensuring consistency of maps across continental and regional scales (Figure 2).
- Open source:** ease the future addition of footprints from other volcanoes. The ETHM project is intended as a multi-step and long-term collaborative initiative, where the scientific community is encouraged to progressively populate the catalog of footprints.
- Replicable:** the ETHM methodology can be exported to other parts of the world.

Figure 2. FALL3D computational domains for the ETHM. Footprints from all volcanoes share a same continental-scale domain at 10 km grid resolution whereas 4 regional nests at 2 km grid resolution are considered for the fallout deposit footprints.

3. ETHM workflow and catalog of footprints

A Common Workflow Language (CWL) file orchestrates the off-line part of the ETHM workflow (Figure 3), which consists of:

- Scenario sampling:** sampling of ESPs within a wide range of plausible scenarios. Sampling is done using the Optimal Latin Hypercube Sampling (OLHS) for: i) eruption start timestamp, ii) tephra erupted mass, iii) eruption duration, iv) standard column height deviation, v) magma viscosity and, vi) Suzuki parameter. The rest of ESPs are inferred using empirical relationships (Figure 4).
- Model inputs:** automated generation of FALL3D model inputs for sampled scenarios. Includes the downloading and cropping of 30 years of ERA-5 meteorological data over the European domain (4.7 TB of data).
- Footprint generation:** for each target volcano and domain 2209 scenarios were simulated running FALL3D on the MN5-ACC supercomputer, using 1 computing node (4 NVIDIA H100 GPUs) per footprint. A total of 53016 footprints were generated for 3 threshold values of concentration (0.2, 2 and 10 mg/m³) at relevant flight levels and 3 threshold values of deposit load (1, 10 and 100 kg/m²).
- Footprint aggregation and storage:** footprint files aggregated by natural months and stored in the CINECA Simulation Data Lake (SDL) to populate a first version of the ETHM catalog of footprints (Figure 5).

Figure 3. Workflow steps of the ETHM, divided into off-line (top) and on-line (bottom) parts.

Figure 4. Scenario sampling results for Vesuvius volcano where each dot represents one of the 2209 footprints. (a) Assumed ranges for tephra erupted mass and eruption duration considering 3 eruption classes: Strombolian (class 1, green dots), sub-Plinian (class 2, red dots) and Plinian (class 3, blue dots). (b) Resulting Mass Eruption Rates (MER) and eruption column heights above vent level (a.v.l.). The dashed line shows the "Mastin-like" power law for reference. The two inset zoom plots illustrate how eruption classes can mix when considered in terms of MER and column height, even if they are disjoint in terms of mass and duration. This is a consequence of the non linear relationships among different ESPs.

Figure 5. Footprints are stored in the CINECA Simulation Data Lake (SDL). The SDL provides a cloud-based storage and management platform, making large-scale simulation datasets discoverable, reusable, and repeatable for the scientific community, particularly in the Solid Earth and geophysical domains. The 53016 footprints and associated metadata from the 12 volcanoes are grouped in 288 files occupying a total of about 65 GB of disk space.

The catalog of footprints is available under the CC-BY-4.0 license at <https://sdl.hpc.cineca.it>

4. Hazard mapping

Figure 6. Example of a single footprint for Katla volcano (Iceland).

Right: concentration footprints for 3 thresholds of 0.2 (blue), 2 (brownish) and 10 (reddish) mg/m³ at FL layers SFC-FL050 and FL250-FL400 and arrival times (in h) for the 0.2 mg/m³ concentration threshold at SFC-FL050 and FL250-FL400.

Top: ground load footprint for 3 thresholds of 1 (blue), 10 (brownish) and 100 (reddish) kg/m² and deposit accumulation times (in h) for the 1 kg/m² load threshold.

Given PDFs for a given time window, footprints are combined to produce single and multi-volcano:

- Probability maps** giving the probability to exceed a given hazard intensity measure.
- Weight-averaged percentile maps** giving the intensity of a hazard.
- Arrival (accumulation) maps**, giving the averaged time needed to exceed a concentration (a load) threshold.
- Persistence maps**, giving the averaged time during which a concentration threshold has been exceeded.

Figure 7. Example of mapping for Vesuvius on the European domain and flight level layer FL205-FL400. Left: probability to exceed a concentration of 2 mg/m³. Center: disruption persistence time for the same threshold (in h). Right: concentration contours (in mg/m³) for the 16% percentile.

Figure 8. Example of deposit mapping for Vesuvius on the Italian regional domain (red box). Left: probability to exceed a deposit load of 10 kg/m². Right: isomass contours (in kg/m²) for the 16% percentile.

5. Summary and next steps

- First version of the European Tephra Hazard Map (ETHM), an initiative of the EuroHPC ChESEE Center of Excellence to facilitate single and multi-volcano hazard mappings consistent across scales and volcanoes.
- A pre-computed catalog of footprints stored in a Simulation Data Lake (SDL) allows to decouple the modelling part of the PVTHA workflow, which normally requires of dedicated HPC resources and skills, from the downstream PDF-driven mapping.
- The first version of the ETHM populated the catalog with more than 53 thousand footprints from 12 European volcanoes.
- A lightweight post-process service is used to create or update different typologies of maps by blending subsets of footprints in the catalog.
- Next steps will export the methodology to other regions of the world, including Mexico and New Zealand.
- AI-driven models for tephra transport and deposition are almost untapped and the synthetic catalog of footprints offers a first training dataset to start exploring this path.