

Modelling of volcanic gas and ash emissions for eruption forecasting and probabilistic hazard assessment

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Conference on Volcanic Processes: a Variety of Length and Time Scales



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International Centre
for Theoretical Physics



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Introductory background

Why do we model atmospheric volcanic ash (tephra) and gas emissions?

Impacts of tephra fallout

- Damage on buildings and infrastructures.
- Disruption of roads and supply networks.
- Agriculture and livestock.
- Airports (disruption, time-consuming and expensive cleaning operations).



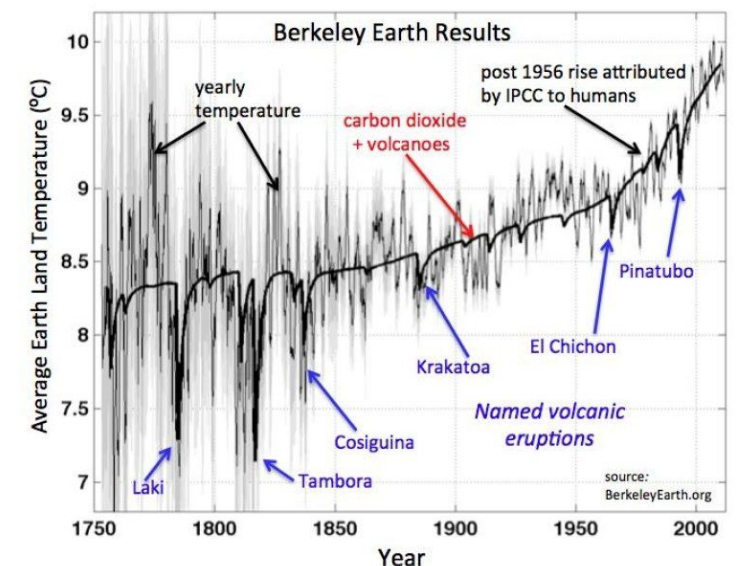
Impacts of fine ash/gas longer-range dispersal

- Impacts on airplanes (turbine blades, windscreens, fuselage, navigation instruments, corrosion, potential engine stall).
- Air quality levels (respiratory system, irritation of skin, eyes, soft tissues, etc).
Impacts on air quality can be very persistent (years) in case of ash resuspension.



Impacts on climate

- Larger eruptions can inject aerosols to the stratosphere causing climatic impacts.
- Sulfur dioxide (SO₂) and hydrogen sulphide (H₂S) react photochemically originating sulfur aerosols that reflect incoming solar radiation.
- This volcanic winter effect is clearly visible in the climatic record.



Source: Berkeley Earth

Ash (tephra) and gas dispersal models

Atmospheric dispersal models are used to:

- Model volcanic ash / gas clouds (cloud trajectory, airborne concentration).
- Model the fallout deposit.

Popular models in volcanology include (not exhaustive list):

Type of model		Approach	Model	Main developer
Semi-analytical models	• Based on approximations • Traditionally (up to 2010s) used for hazard mapping and / or deposit inversion	Gaussian	HAZMAP	CSIC - INGV (Spain / Italy)
			TEPHRA2	USF (USA)
			ASHFALL	GNS (New Zealand)
Numerical models	• Based on numerical solutions of the transport equations • More computationally intensive (more recently also used for hazard mapping)	Eulerian models	ASH3D	USGS (USA)
			FALL3D (*)	CSIC - INGV (Spain / Italy)
			MOCAGE (*)	MeteoFrance (France)
		Lagrangian models	FLEXPART (*)	NILU (Norway)
			HYSPLIT	NOAA (USA)
			NAME (*)	UK Met Office (U.K.)

(*) also cover gas dispersal

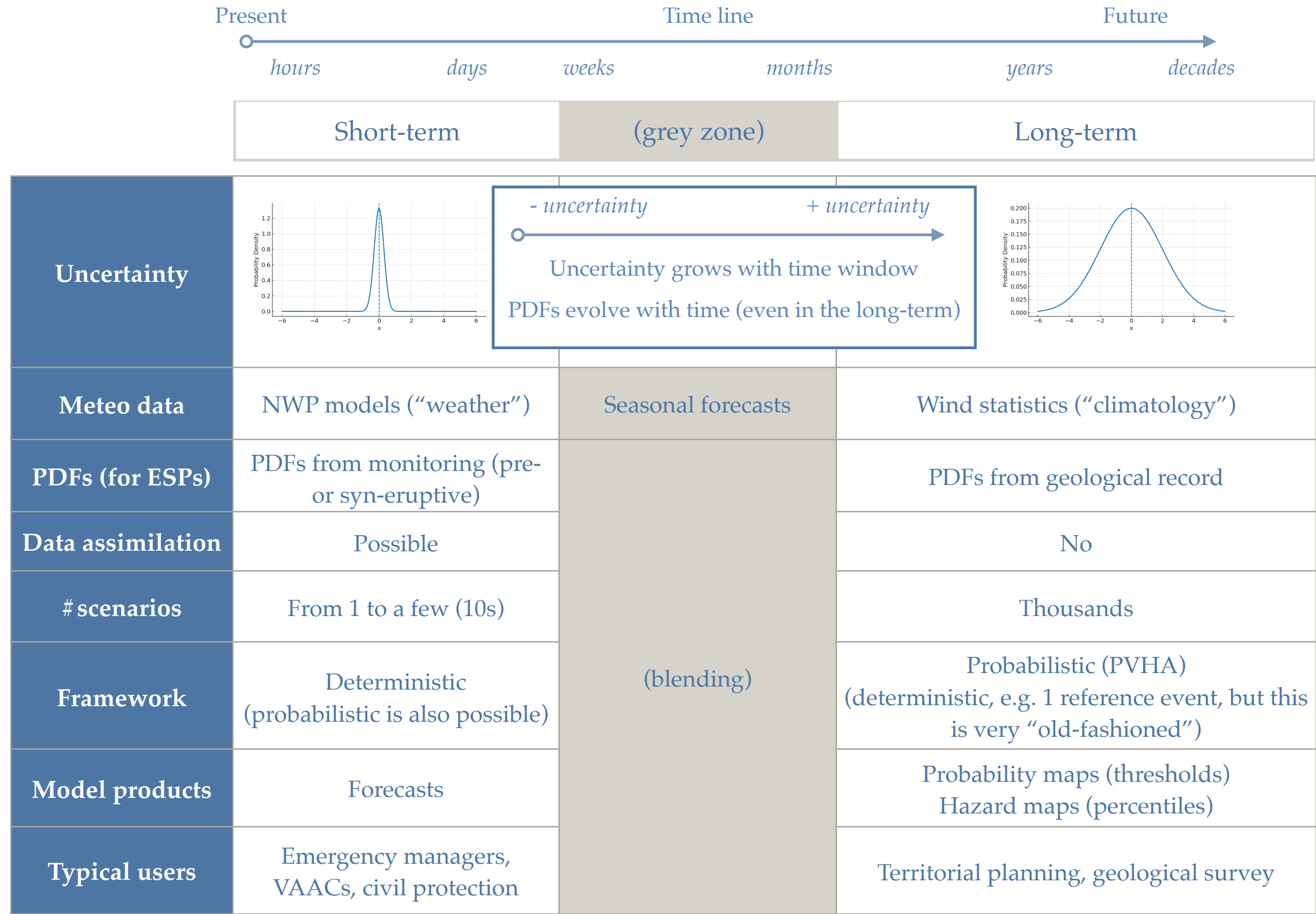
Ash (tephra) and gas dispersal models

Many models but... all built upon the same **3 ingredients**:

1	Meteorological data	Describes the 4D state of the atmosphere (wind field, air density, temperature, moisture, precipitation rate, etc); provided by NWP models • Global / Regional / Local-scale models. • Forecast / Re-analysis.
2	Eruption Source Parameters (ESPs)	Define the source term (volcanic plume) in time and space; this is the eruption scenario • Typically, the emission model is embedded in the dispersal model. • ESPs include both plume characteristics (height, MER, duration, etc) and particle properties (TGSD, shape, density).
3	Dispersal model	Accounts for the physics and, depending on the model, includes terms like: • Advection by wind. • Turbulent diffusion (different parameterisations). • Particle settling velocities (different parameterisations). • Dry and wet deposition mechanisms (different parameterisations). • Eventually, particle aggregation (different aggregation models). • Eventually, chemical reactions and / or phase changes.

Uncertainties exist in all these 3 components and strongly depend on the **TIME SCALE**.
This time-dependency of uncertainties explains the different strategies that, traditionally, have been adopted for short and long-term modelling.

Modelling strategies for short and long-term (end members of a continuum)

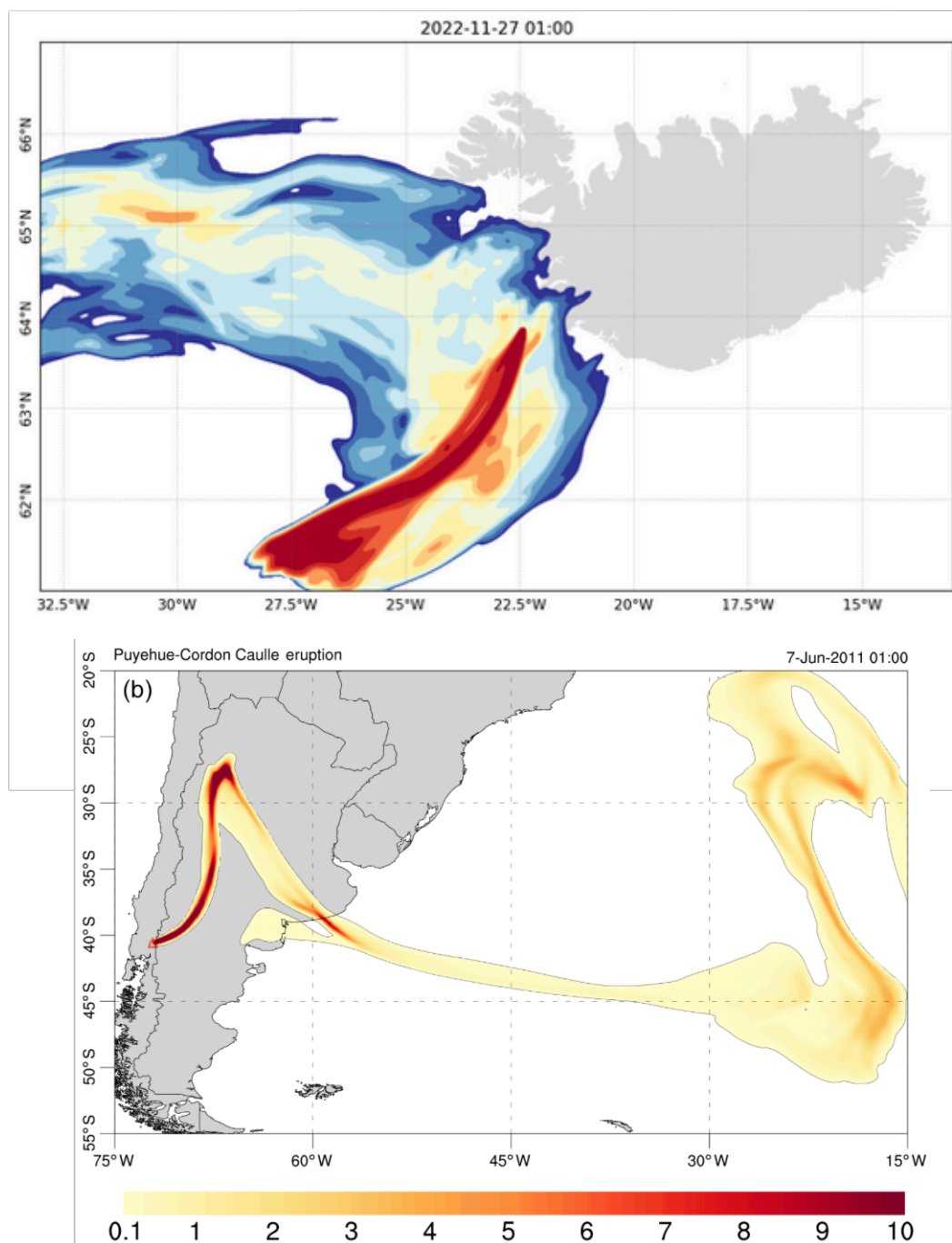


Examples of products

Short-term

Deterministic forecasts

- Tephra fallout.
- Airborne ash/gas concentration.
- Typically done during eruptions.



Long-term

Probability maps

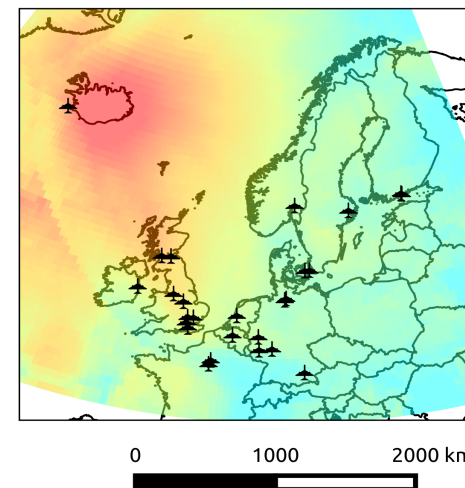
- Ground load above a threshold (e.g. 100 kg/m²).
- Presence of ash above a concentration threshold (e.g. 2 mg/m³) at any FL.

Hazard maps

- Percentile scenario for ground load/airborne concentration.

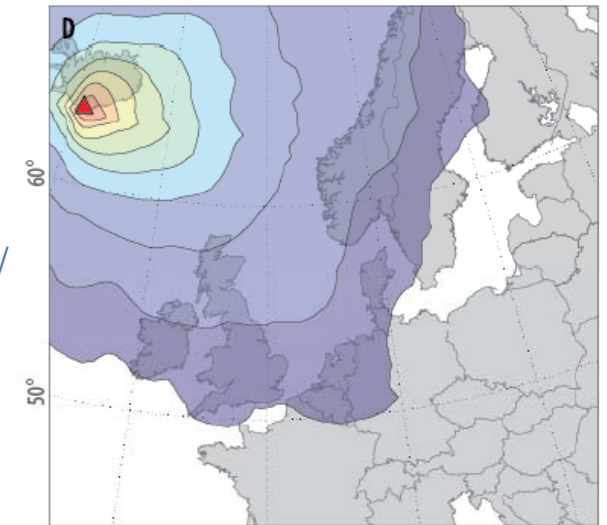
Arrival time and persistence

- Estimation of the reaction time and disruption severity.



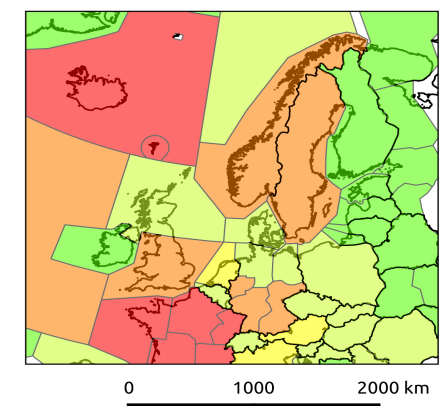
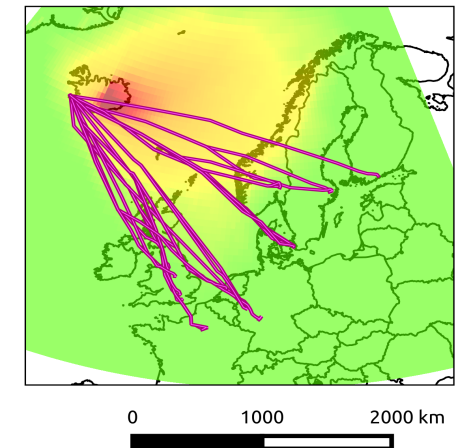
Flight Information Regions (FIRs)

- Impact on airspace sectors.



Probability of disruption

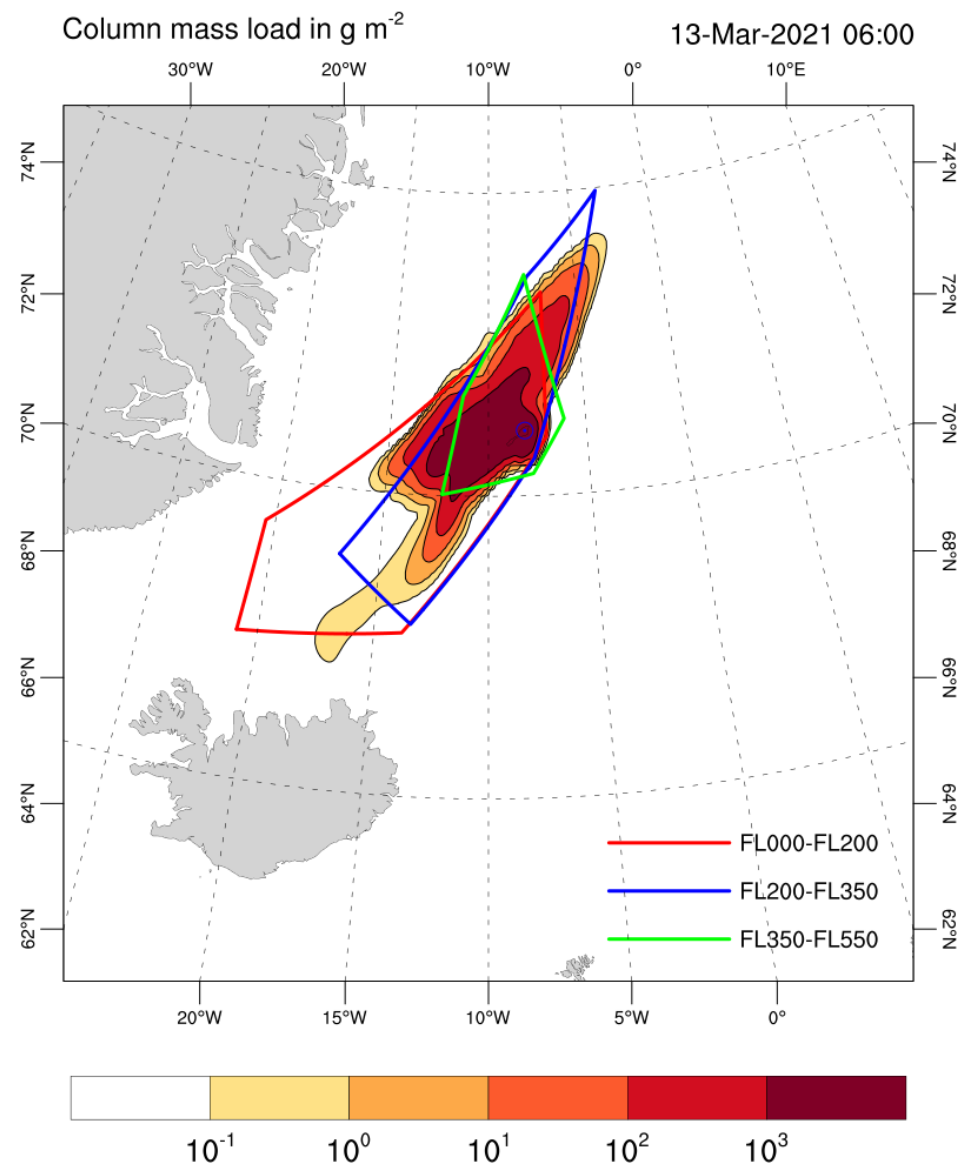
- For strategic flight routes or airports.



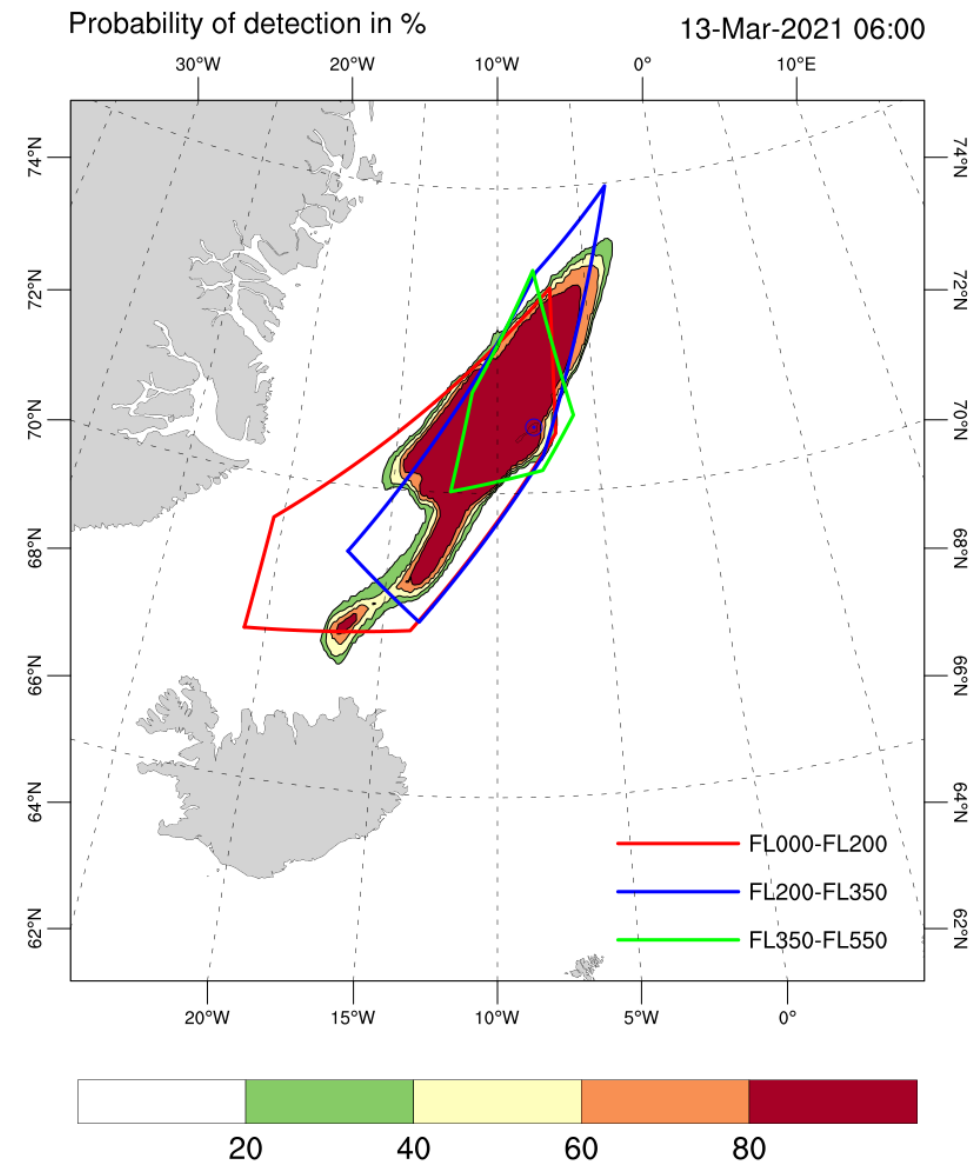
Advances in volcanic cloud modelling (last decade)

1. **Ensemble-based runs** (with the ensemble members spanning the ESPs uncertainty range). Allow for:

- Deterministic forecasts (e.g. ensemble mean) with uncertainty quantification (e.g. ensemble spread).
- Probabilistic forecast (counting the number of members that verify certain condition).



FALL3D ensemble-based deterministic forecast
(color contours show the ensemble mean)

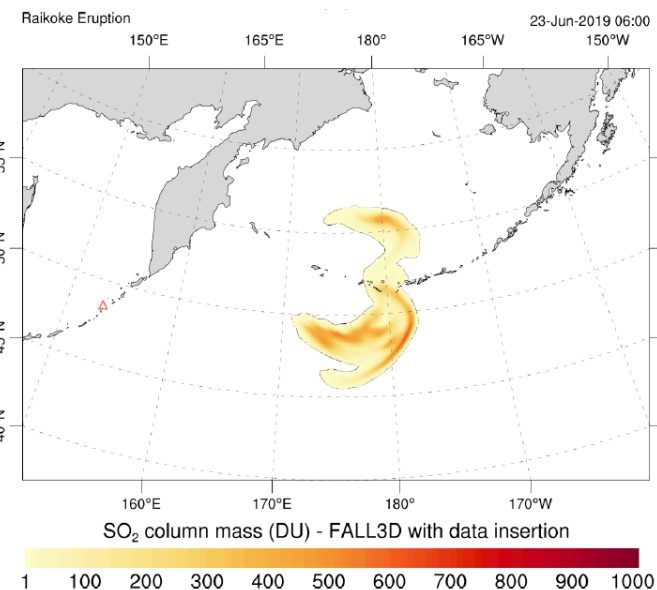
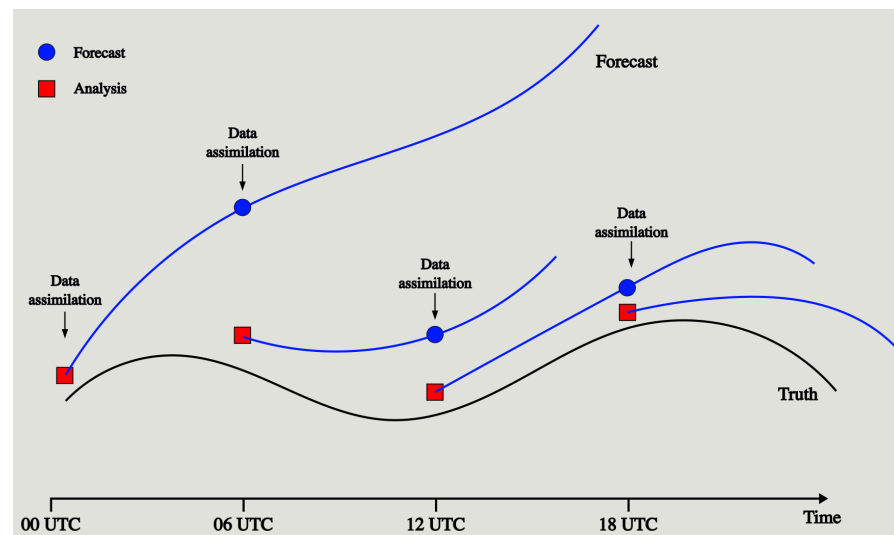


FALL3D ensemble-based probabilistic forecast
(color contours show probability of detection)

Advances in volcanic cloud modelling (last decade)

2. Model Data Assimilation (DA) strategies:

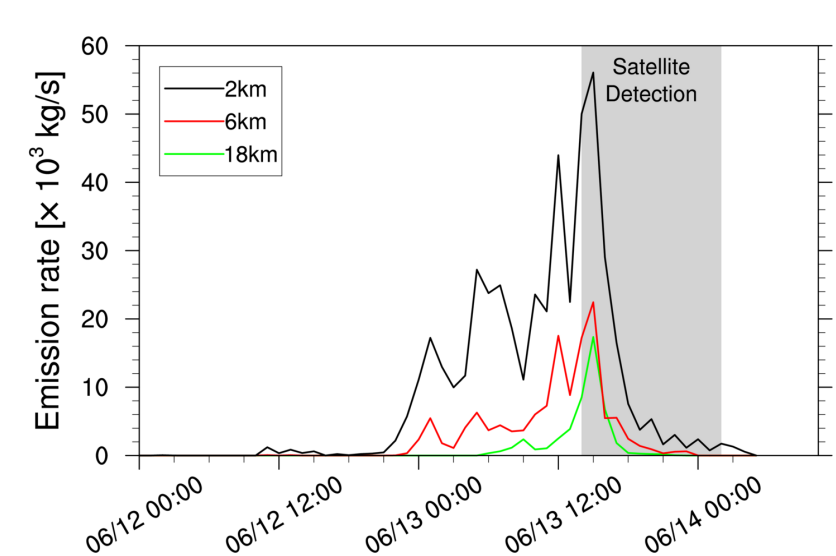
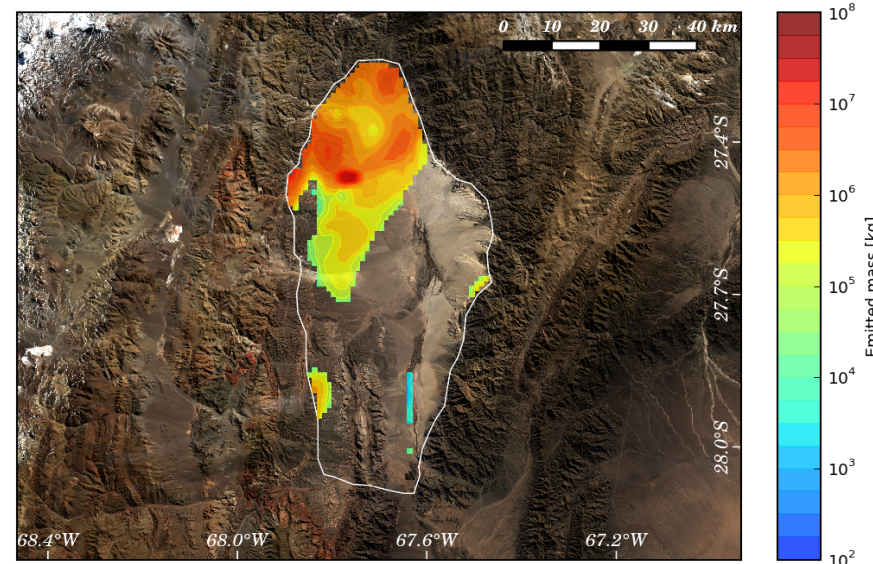
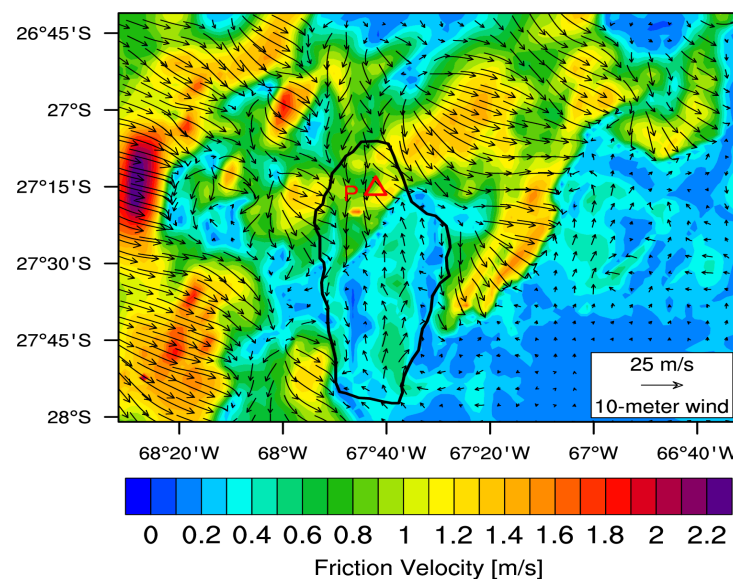
- Data Insertion.
- Source term inversion (more suitable for Lagrangian models).
- Sequential DA (use of Kalman filters). Promising alternative for assimilation of volcanic aerosols but with limitations leading to suboptimal filter performance.



FALL3D with data insertion.
Results at the same instant
(insertion was done at 22 June
18:00 UTC, 12h before the plot)

3. Modelling of fine ash resuspension:

- Developing and testing of emission schemes.



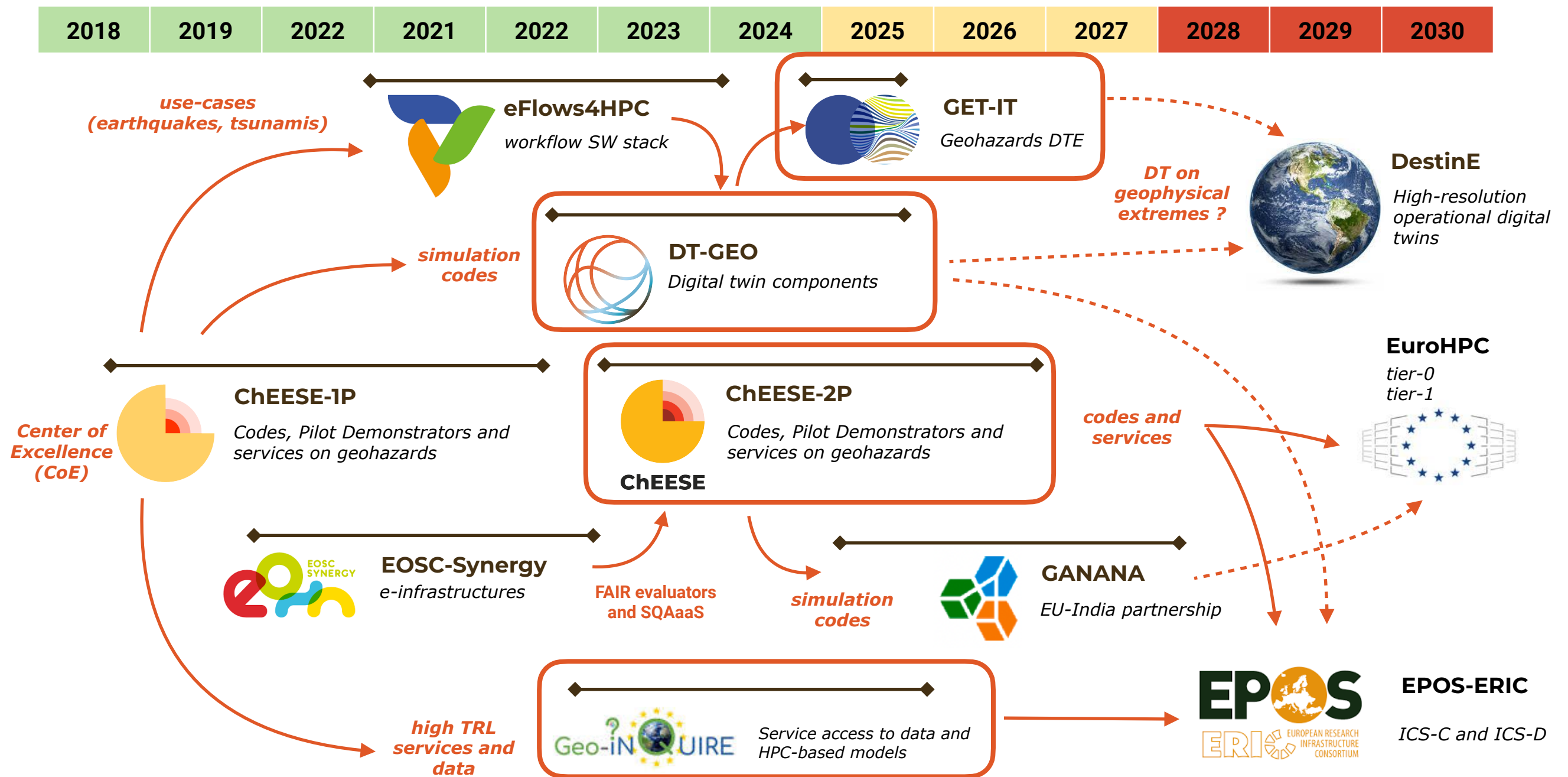
Trends in all Natural Hazards

(examples from 4 EU-funded projects)

1. **How HPC can help?** (the EuroHPC ChEESE CoE)
2. **Digital Twins of Earth's systems** (the DT-GEO project)
3. **Federation of services and data lakes** (the Geo-INQUIRE project)
4. **Towards Destination Earth** (the GET-it project)



An ecosystem of interrelated projects with long-term (2028-2030) ambitions



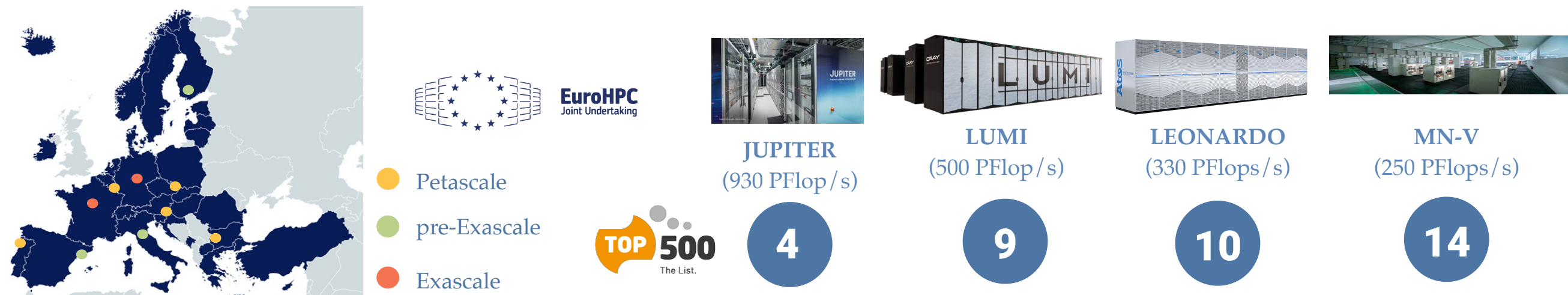
These large projects (>40M€ in total) address several Natural Hazards, but all have applications on modelling volcanic emissions

1. How High Performance Computing (HPC) can help?

Common ingredients of both short and long-term modelling strategies

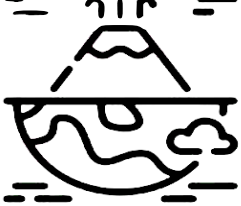
Common ingredients of both short and long-term modelling strategies				
Upstream	HPC			Downstream
1 Data	2 Models Scenarios	3 Workflow Orchestration	4 Infrastructure HPC/Cloud	5 Other Postprocess/Services
HPC (in general)		Solve larger (e.g. higher resolution) and / or more complex problems (e.g. better physics)		Large datasets (good for AI)
Short-term	Ingest data streams	Reduce the overall time-to-solution		Urgent Computing services
Long-term		Many (thousands) of physics-based scenarios		Map large uncertainties

The current EuroHPC Centers of Excellence (CoEs)



EUROHPC-JU-2021-COE-01-01 4 CoEs (type 1)	MaX-3	Materials	   
	SPACE	Astrophysics	
	Plasma-PEPSC	Plasma simulations	
	CEEC	Fluid Dynamics	
EUROHPC-JU-2021-COE-01-02 6 CoEs (type 2)	ChEESE-2	Geosciences	     
	BioExcel-3	Biomedicine	
	EXCELLERAT-2	Engineering applications	
	HiDALGO-2	Big data technologies	
	ESiWACE-3	Weather and climate	
	MultiXscale	Multiscale use cases	
EUROHPC-JU-2023-COE-01 2 CoEs	POP3	Performance productivity	 
	EoCoE-III	Energy	
EUROHPC-JU-2023-COE-03 2 CoEs	dealiiX	Digital twins of organs and tissues	 
	MICROCARD-2		

The CoE in geophysics (and geohazards)

	Earthquakes	Volcanoes	Tsunamis	MHD	Geodynamics	Glaciers
ChEESE-1P (2018-2022)						
ChEESE-2P (2023-2026)						

ChEESE sustains on 3 pillars

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Flagship codes

Open source community codes on seismology, tsunamis, volcanoes, geodynamics, magneto-hydrodynamics, and glaciers

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Pilot Demonstrators

Workflows that address underpinning capability / capacity / UC exascale computational challenges

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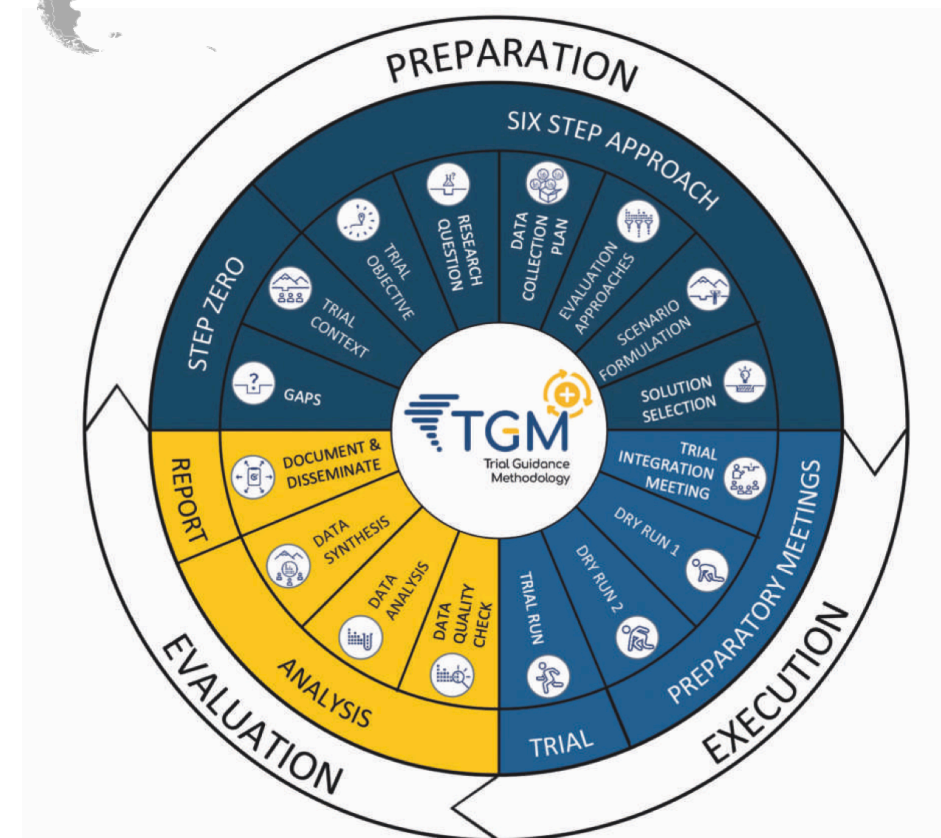
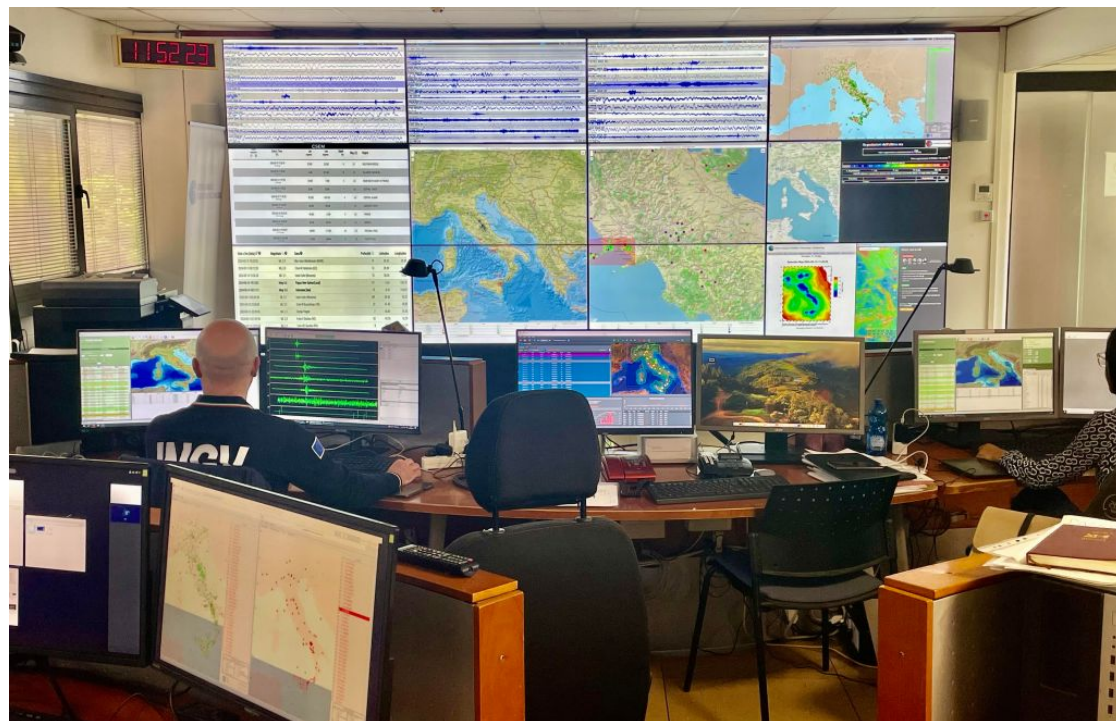
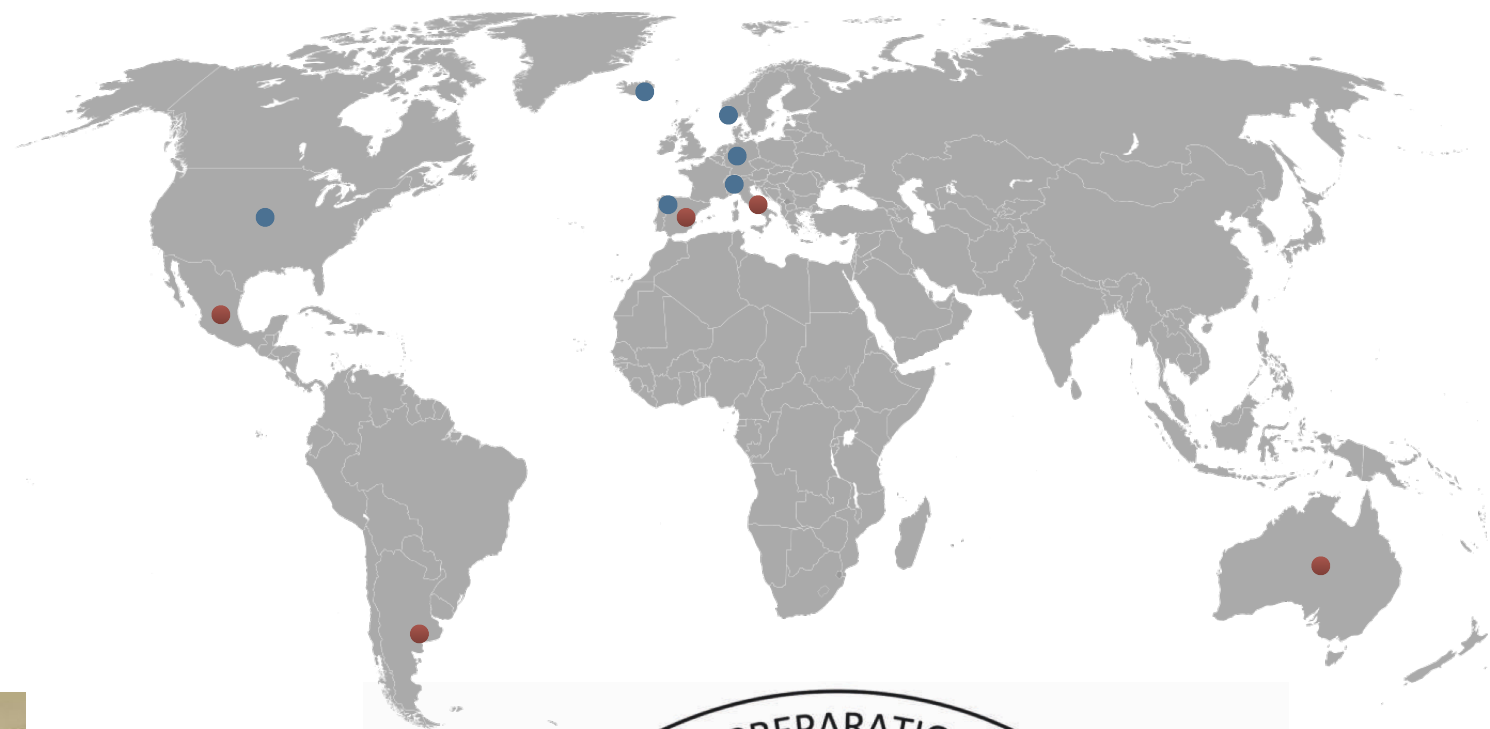
Simulation Cases and Services

Enabling of services on socially-relevant aspects of geohazards like urgent computing for disaster response, early warning systems, and long-term hazard assessment

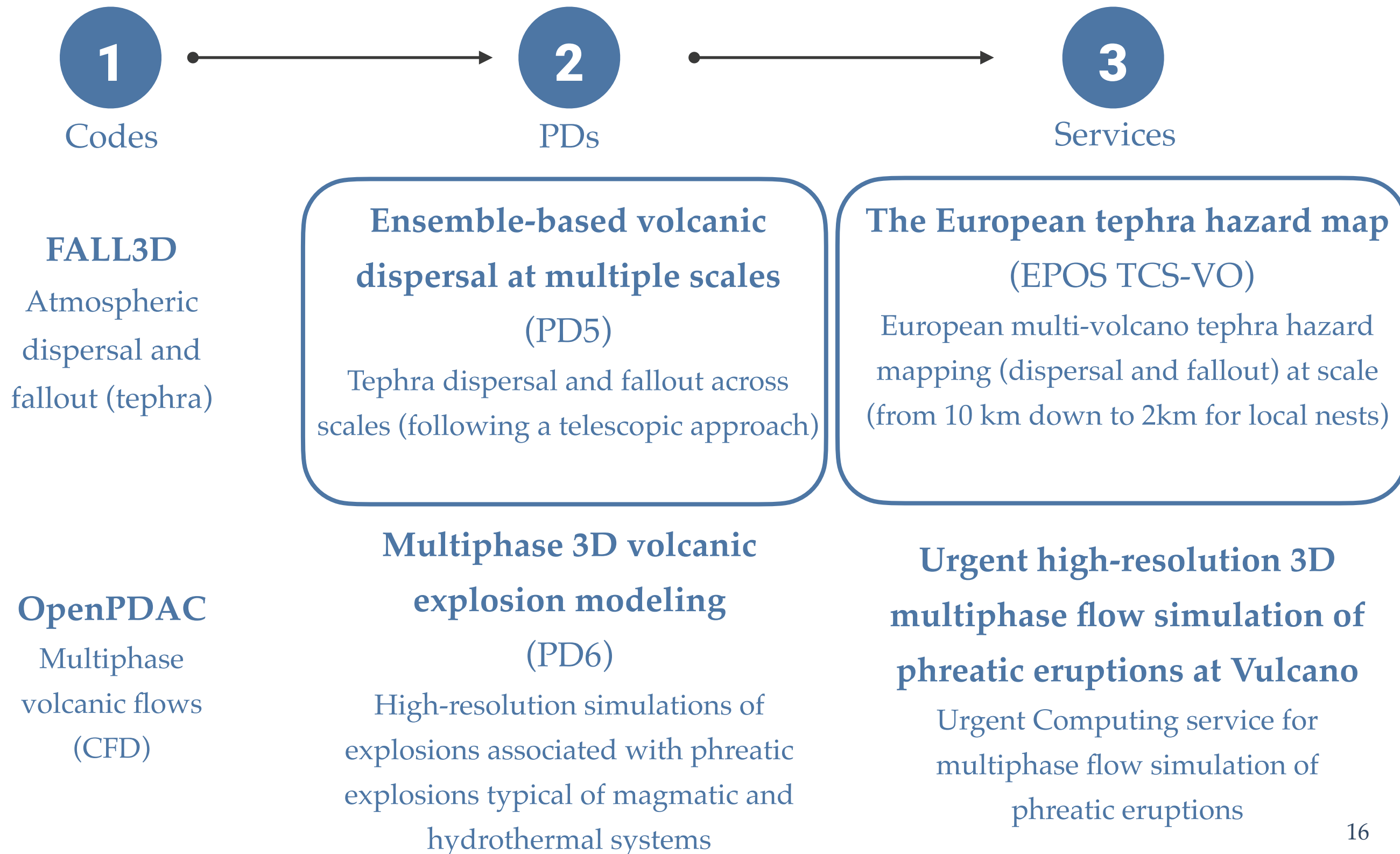
Pilot Demonstrators achieving high (7-9) Technology Readiness Levels (TRL) will be showcased through **live TRIALS** in order to:

- Trials test the new technological solutions and innovations, and collect user feedback to improve the solutions.
- Trials focus on a problem in daily operations and initiate the process of assessing solutions.

The so-called Industry and Users Board (IUB) plays an important role in proposing, **driving and evaluating trial exercises** and related services



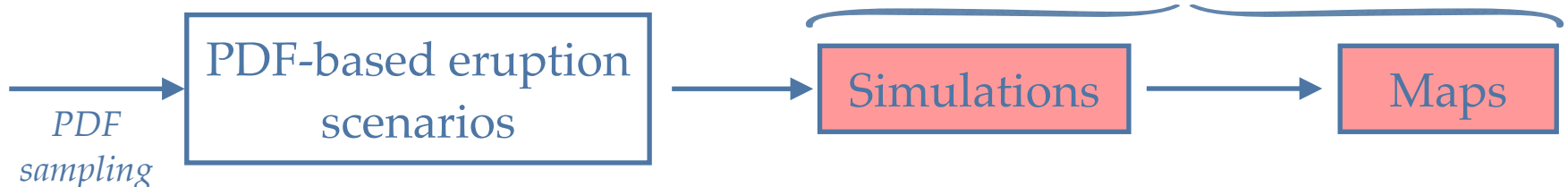
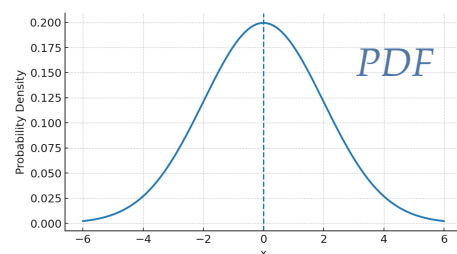
Which volcanic hazards are covered by ChEESE?



Motivation (current caveats of long-term PVHA)

- PVHA based on numerical models is computationally expensive.
- Many users do not have skills and/or easy access to HPC resources.
- Geological record:
 - Has irregular coverage and heterogeneous data (VEI, intensity, column height).
 - Poor binning and non-obvious mapping without metadata.
 - As a result, different volcanologists often claim “my PDF (and the resulting maps) is the right one”.
- How to add the time-evolving component of hazard without re-running?
- With some exceptions, PVHA is done for single-volcanoes...

Classical PVHA approach



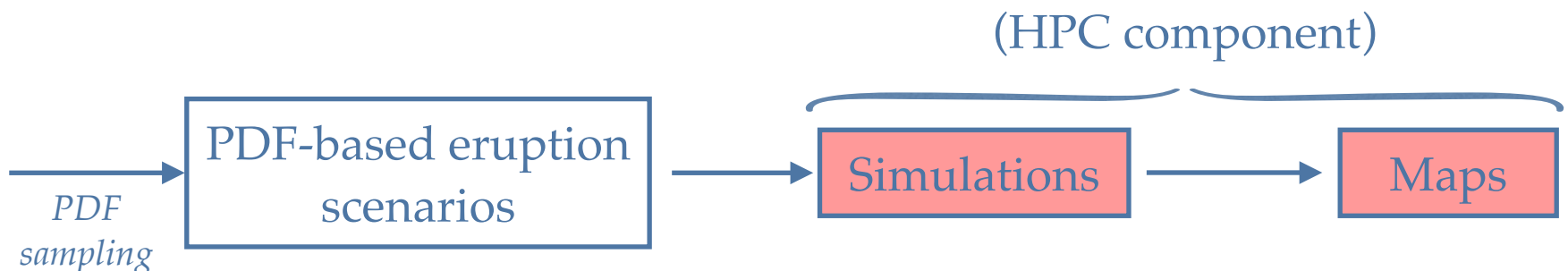
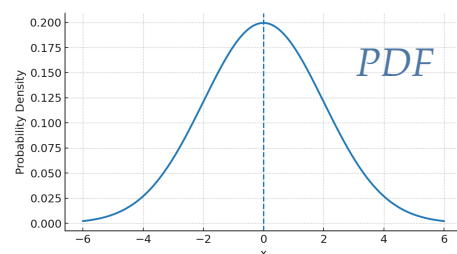
Uncertainty is upstream

HPC is downstream

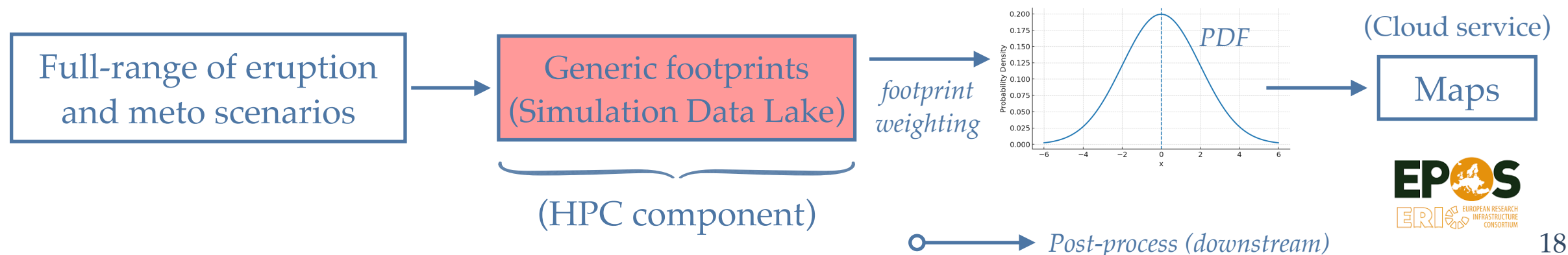
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Classical PVHA approach



Our (novel) approach



The European Tephra Hazard Map (ETHM)

First multi-volcano tephra hazard mapping for Europe:

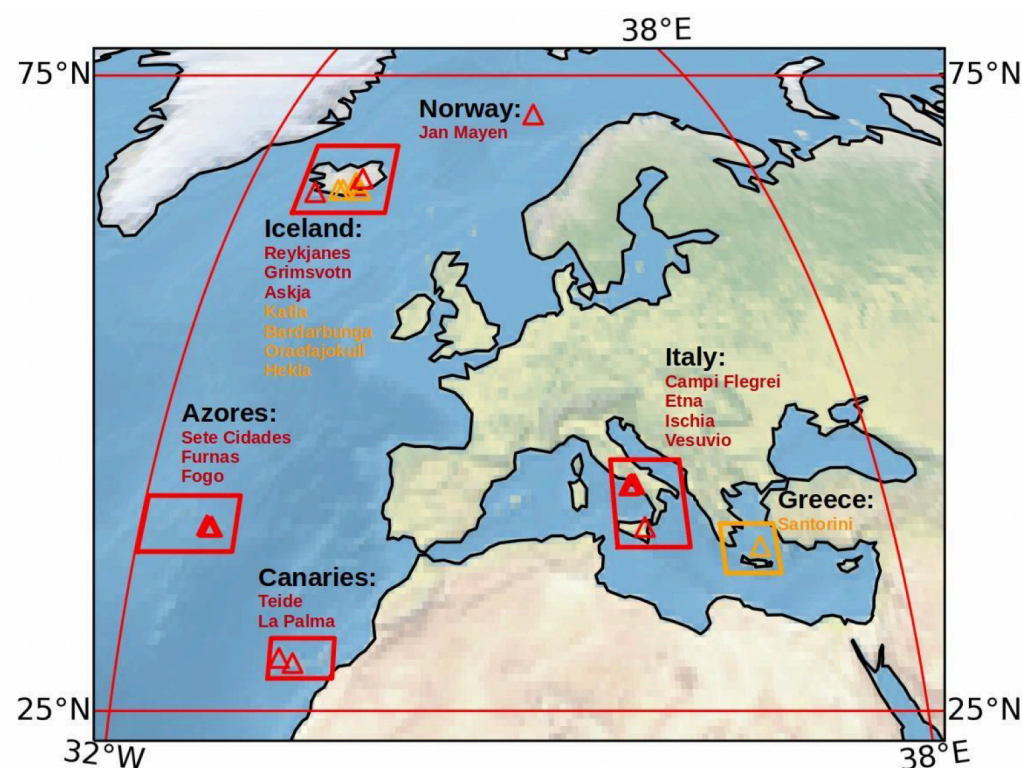
- European domain (10 km resolution): hazardous airspace regions (ash concentration at critical FLs).
- Regional nests (2km resolution): proximal tephra fallout.

The ETHP will adopt and incremental methodology:

- Long-term community effort: ease the addition of more volcanic sources in a future.
- **Updating of maps** whenever new data (e.g. unrest episode, new eruptive records) becomes available (i.e. every time a PDF changes for whichever reason).

Modelling:

- FALL3D model (v9.1) + ERA-5 (30 years).
- First phase (2025): catalogue of >100k footprints from 12 volcanoes (+2 in the pipeline).
- Allocated 120.000 GPU/hours on MN5-ACC supercomputer @BSC (EuroHPC regular access mode).
- Rich embedded metadata and hosting at SDL@CINECA.
- Downstream **lightweight map-generation service** (EPOS TCS-VO).



Italy	CFC, Vesuvio, Ischia, Etna
Iceland	Reykjanes, Hekla, Katla
Canaries	La Palma, Teide
Azores	Sete Cidades, Furnas, Fogo
Norway	Jan Mayen
Greece	Santorini

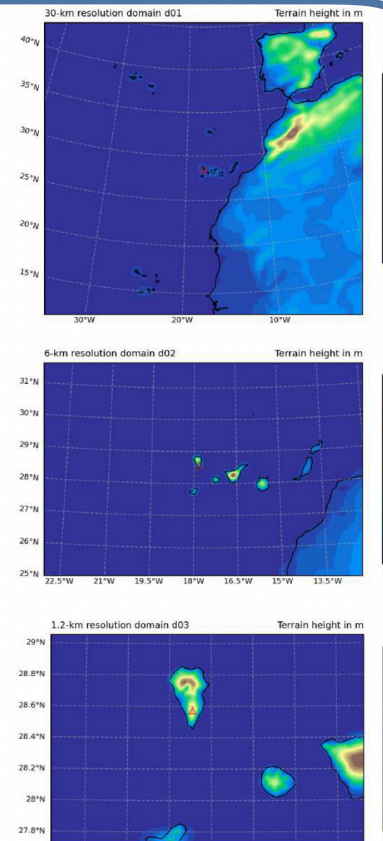
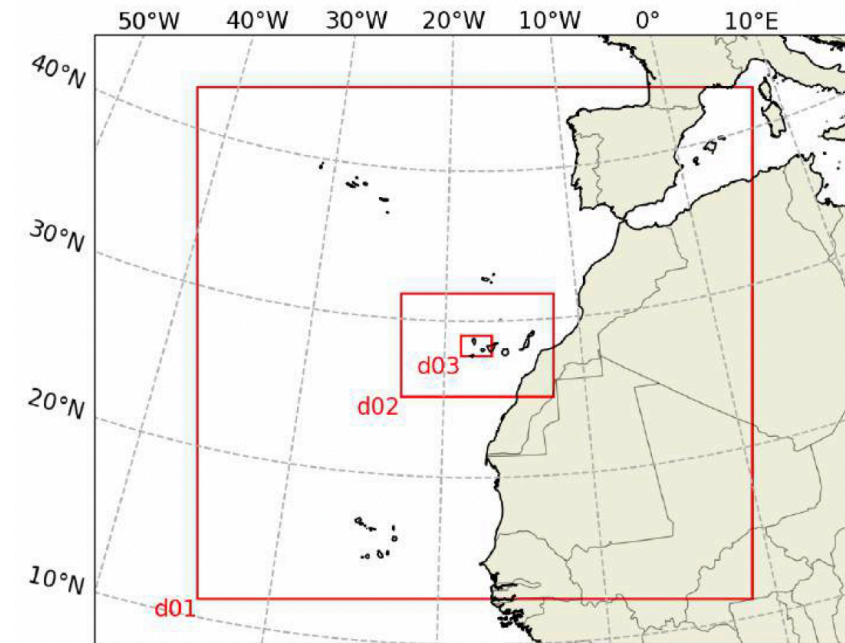
Ensemble-based volcanic dispersal at multiple scales

Simulate the volcanic gas dispersal at local scale:

- FALL3D driven by mass-consistent meteorological downscaling.
- Reanalysis at <1 km resolution of the 2021 eruption of Cumbre Vieja (La Palma).

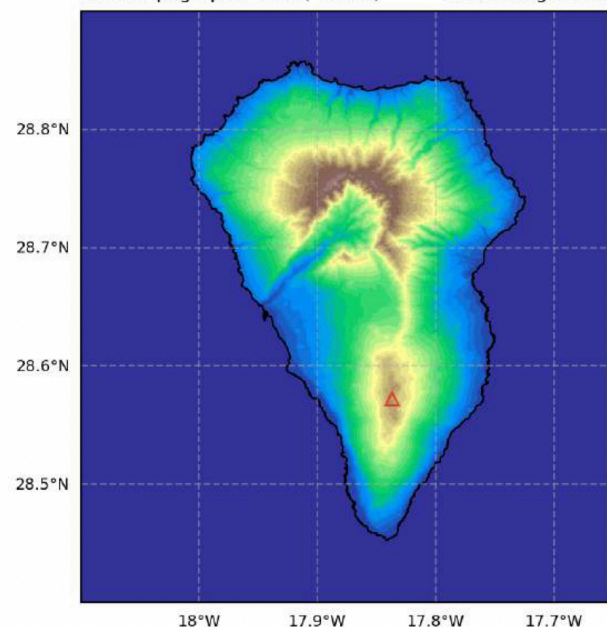


WRF domains with resolution of 30 km (d01), 6 km (d02) and 1.2 km (d03)

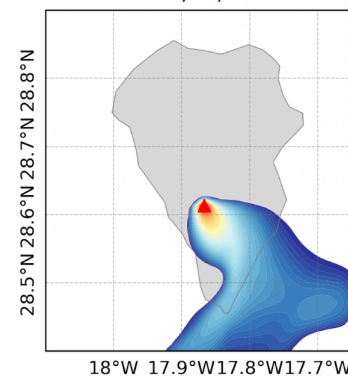


MetPrep used to obtain meteorological downscaling to 600 m

SRTM topographic data (~30 m) Terrain height in m

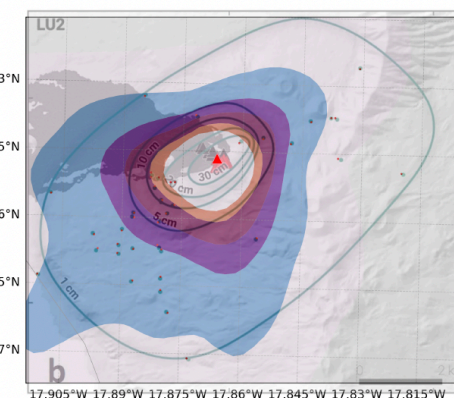
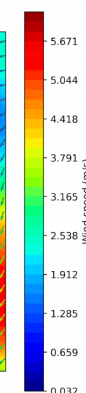
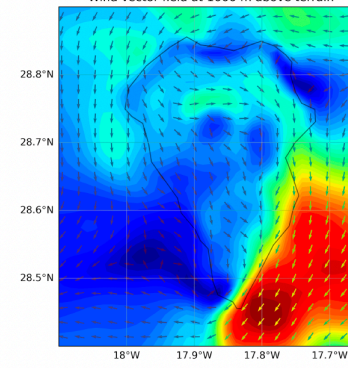


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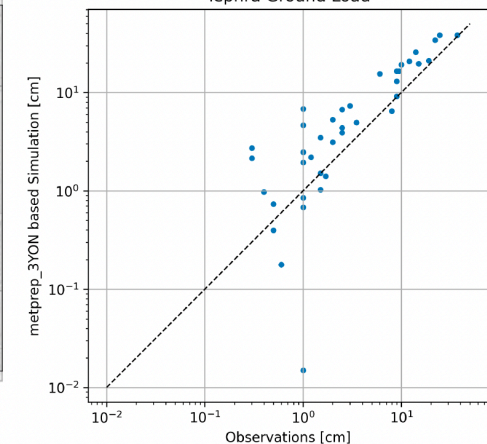
Tephra column mass [$g\ m^{-2}$]

Wind vector field at 1000 m above terrain



Tephra ground load [cm]

Tephra Ground Load

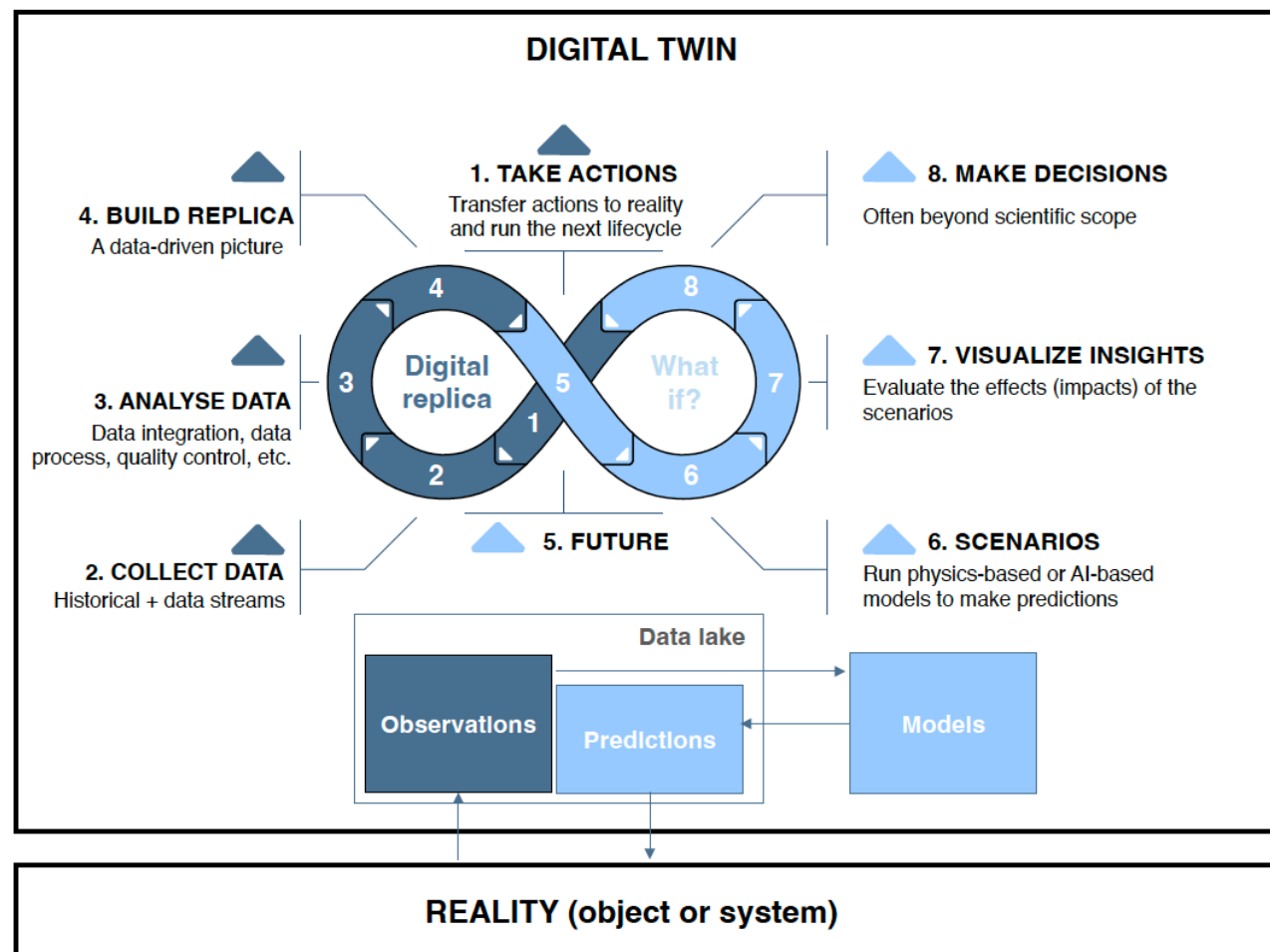
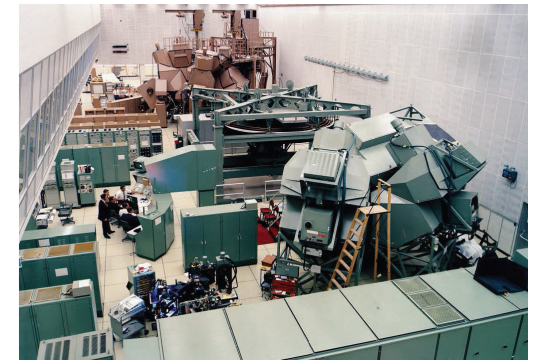


2. Digital Twins of Earth's systems

- The idea of a “**living replica**” was born at NASA during the Apollo Moon program (1962-1972). During the Apollo 13 mission (April 1970), the on-ground “**analogical twin**” was key to help engineers testing solutions to rescue the mission successfully.

A Digital Twin is a **virtual lifecycle environment** that contains:

- A data-informed **digital replica** of a real system,
- Model-based **prediction** capabilities (scenarios) and, ideally,
- Can provide **feedback** (decisions) to modify the real system (i.e. lifecycle loop).




Manufacturing
Mirroring design lifecycle


Health
Personalised medicine


Automotive
Design and improve performance


Urban planning
Augmented reality systems


Wind energy
Wind farms


Detectors
Interferometers, radio-telescopes


Astrophysics
Particle accelerators

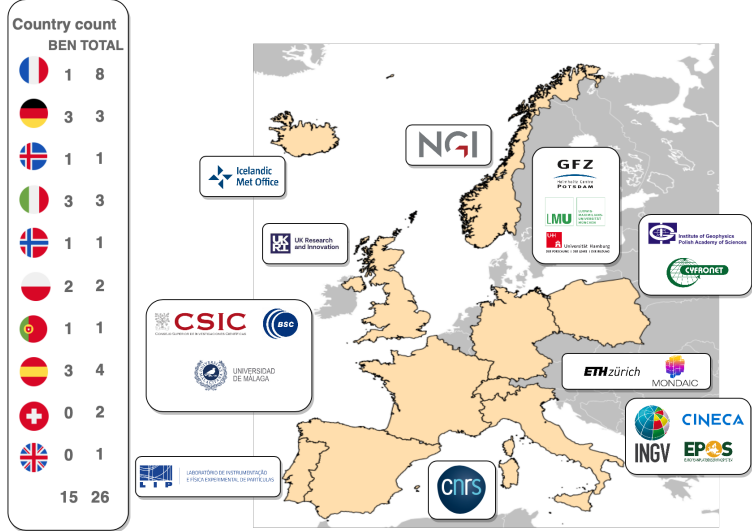

High-energy Physics
Particle accelerators

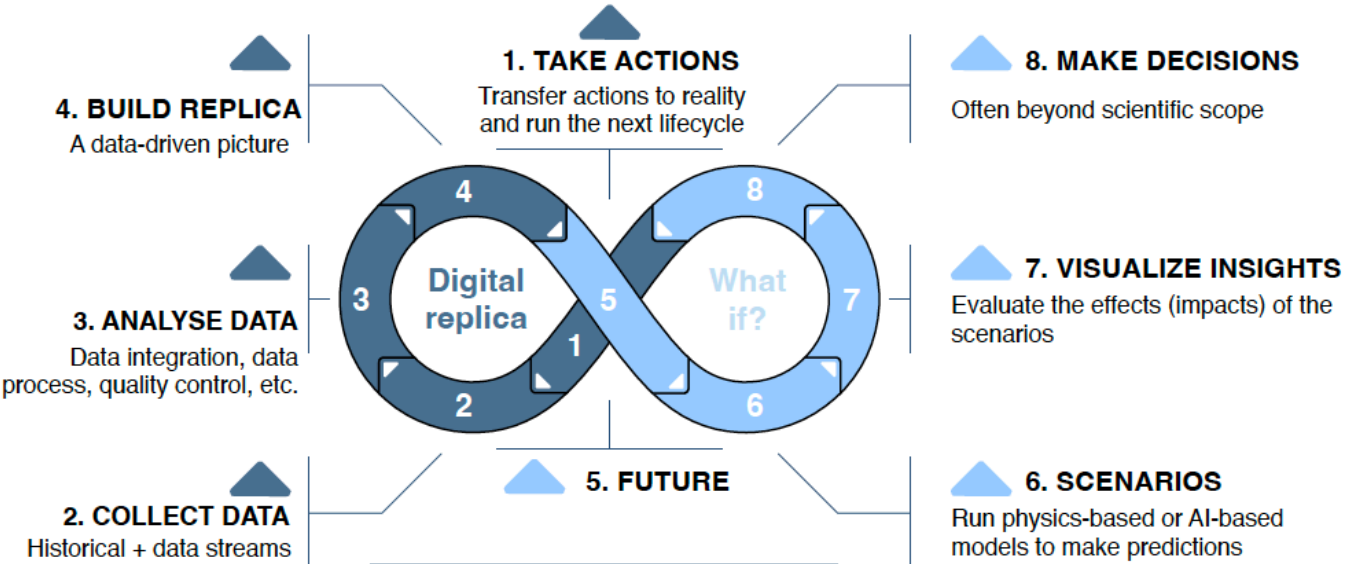
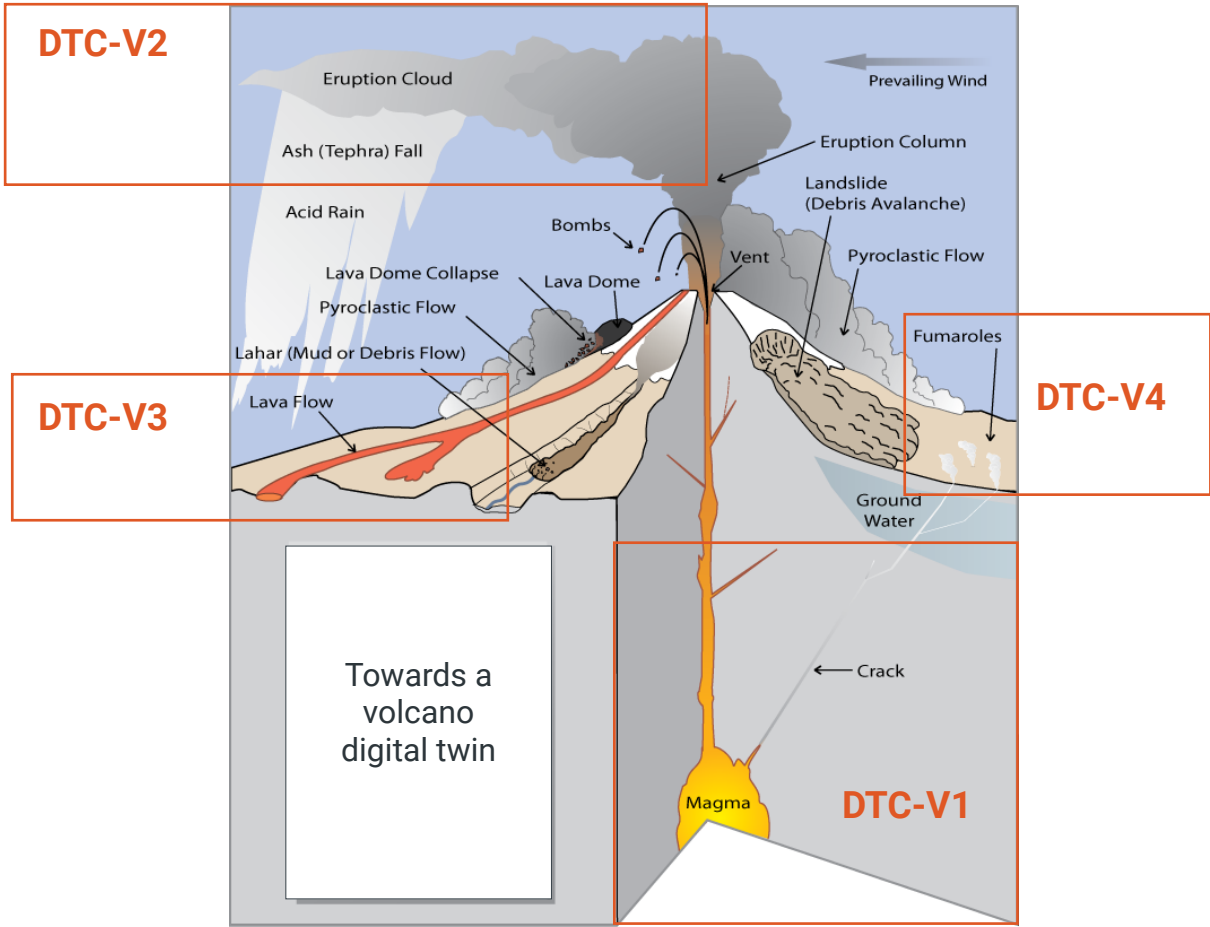

Earth system
DT-GEO and DestinE

- Deploy a pre-operational prototype of **Digital Twin** (DT) on geophysical extremes for its future integration in the Destination Earth (DestinE) initiative.
- Implement 12 self-contained **Digital Twin Components** (DTCs) addressing specific hazardous phenomena from volcanoes, tsunamis, earthquakes, and anthropogenically-induced extremes to conduct precise **data-informed** early warning systems, forecasts, and hazard assessments across multiple time scales.

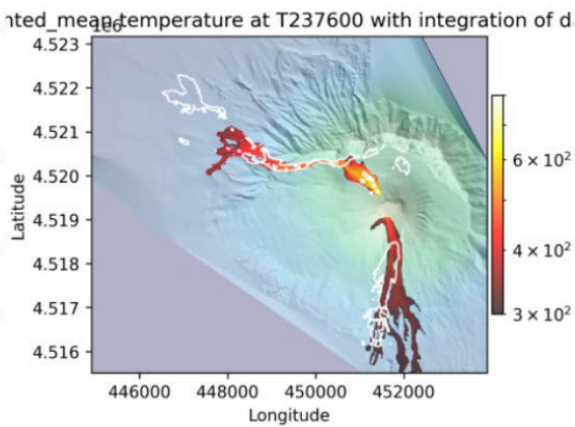
12 Digital Twin Components (4 in volcanology)

1	DTC-V1	Volcano	Volcanic unrest dynamics
2	DTC-V2		Volcanic ash clouds and deposition
3	DTC-V3		Lava flows
4	DTC-V4		Volcanic gas dispersal and deposition
5	DTC-T1	Tsunami	Probabilistic Tsunami Forecasting (PTF)
6	DTC-E1	Earthquake	Probabilistic Seismic Hazard and Risk Assessment
7	DTC-E2		Earthquake short-term forecasting
8	DTC-E3		Tomography and Ground Motion Models (GMM)
9	DTC-E4		Fault rupture forecasting
10	DTC-E5		Tomography and shaking simulation
11	DTC-E6		Rapid event and shaking characterization
12	DTC-A1	Anthropogenic	Anthropogenic geophysical extreme forecasting (AGEF)





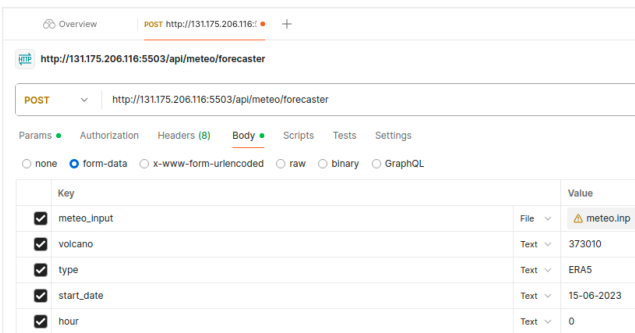
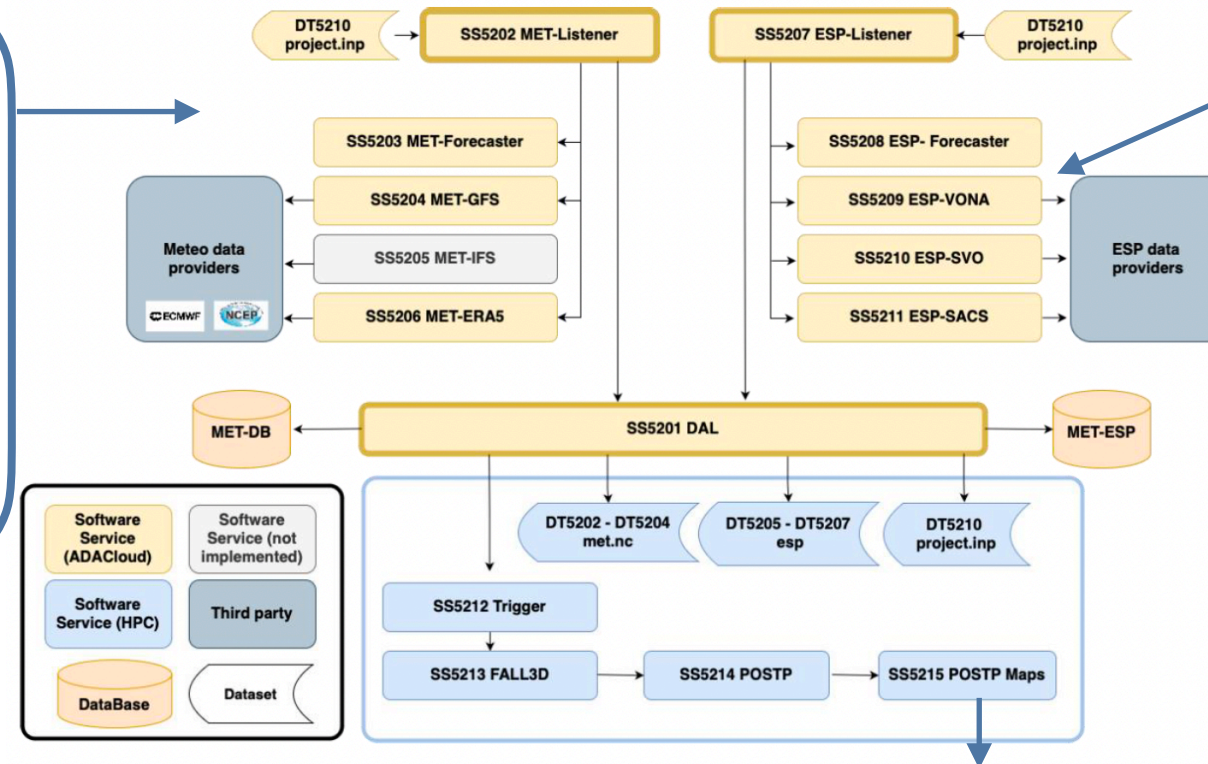
Replica	Triggers (only if an eruption or unrest)	Impacts (what if)	
DTC-V1		DTC-V2	Ash dispersal
		DTC-V3	Lava flows
		DTC-V4	Gas dispersal
State of the volcano based on geophysical monitoring and models		Urgent computing impact assesment combining physics-based models (HPC) and observations	
steps 2-4 of the cycle		steps 5-7 of the cycle	



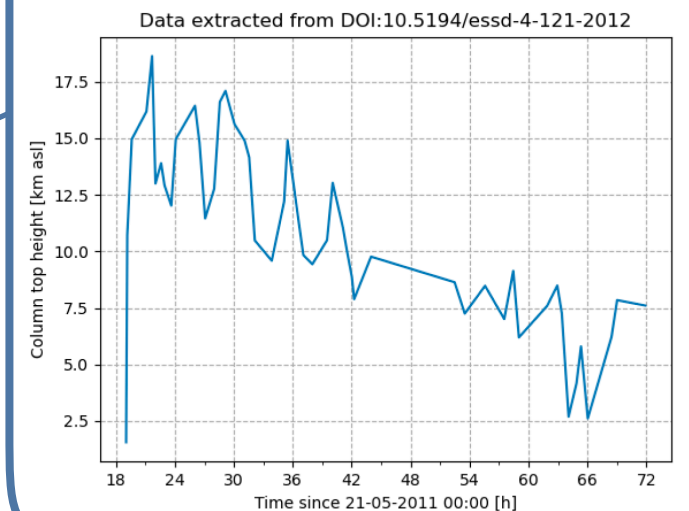
Automate the forecasting of atmospheric dispersal and ground deposition (fallout) of volcanic ash:

- Integrates the FALL3D dispersal model in an ensemble model configuration.
- Probabilistic and deterministic forecasts within a 48-hour time window.
- Diverse observational data sources, including ground-based and satellite-based.
- Improves the reliability of volcanic ash advisories, supporting decision-making.

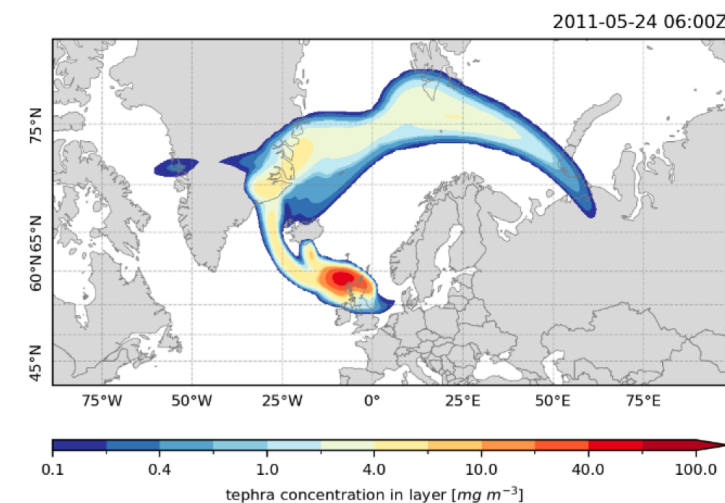
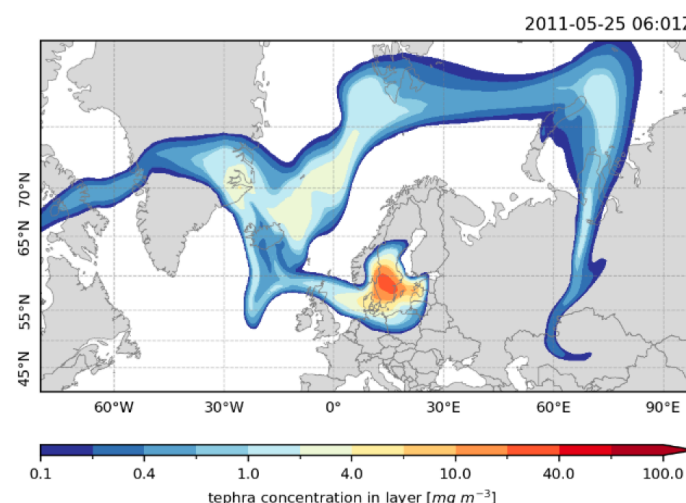
Workflow of interconnected datasets and software services

Time series of column height (IMO radar)

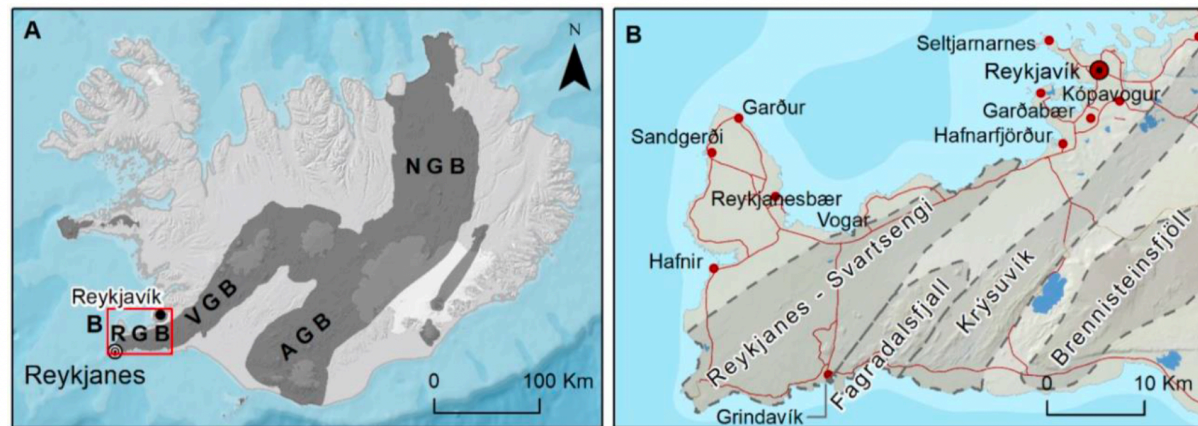


Forecast of the 2021 eruption of Grímsvötn eruption

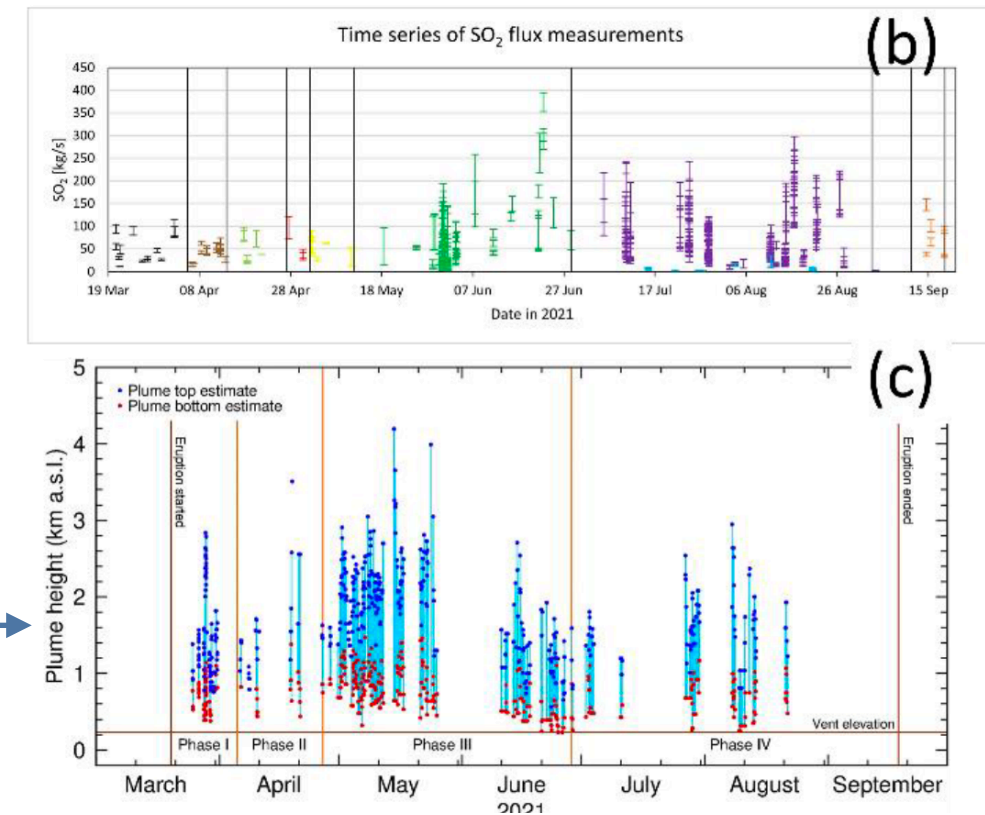


DTC-V4: Short-term volcanic gas dispersion and deposition

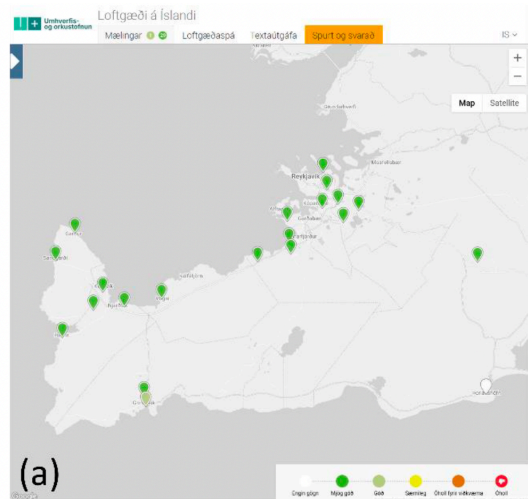
- During effusive eruptions it is common to deal with air quality issues due to the release in the atmosphere of volcanic gases.
- Fagradalsfjall eruption 2021: high concentrations of SO₂ in inhabited areas.
- In Iceland, monitoring techniques often fail in quantifying flux and the height of the injection in real-time (e.g. bad weather conditions).



DOAS and thermal camera observations are discontinuous



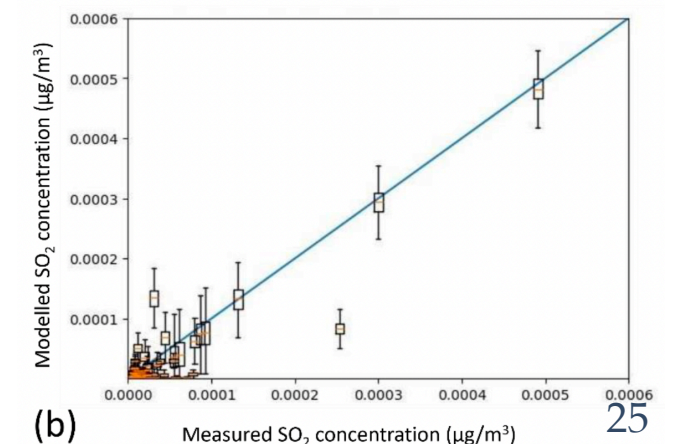
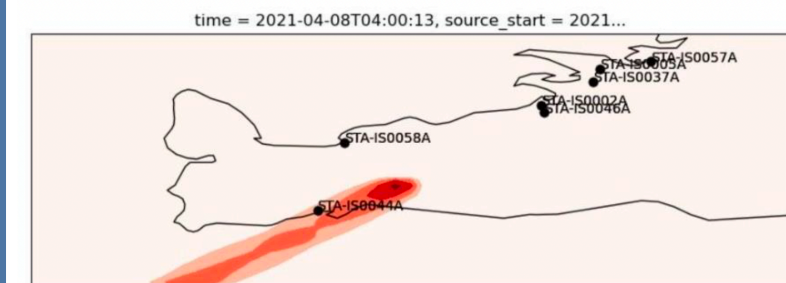
Ground-based air-quality stations operated by the Environmental Agency of Iceland



ML inference

Reconstruction of the ESP posterior distribution (SO₂ flux and plume height),

FALL3D SO₂ forecast



3. Federation of services (towards the concept of MaaS)

What is going-on out there...



	Few years ago...		MaaS	Modelling as a Service (MaaS) concepts
Data	Data is in this excel file: I will send it by email (with an explanation on what each column/row actually means)	→	DaaS	Metadata standards, interoperability, data lakes, federation, integrated data analysis tools (covered by EPOS...to some extent)
Models	The model is in a zipped file: feel free to use it (at your own risk)	→	SaaS	Containers, portability across hardware architectures, CI/CD
Workflows	I write my custom shell and python scripts for everything I need (and it normally works in my platform!)	→	WaaS	Workflows deployed and orchestrated on centralised, cloud-managed, or hybrid (distributed) premises
Infrastructure	I run on my laptop (my institute has a small cluster but it is always busy)	→	IaaS	Cloud computing, storage, network, virtual servers, Infrastructure Manager (IM)
FAIRness level	Well, I do not know exactly (but do not worry, everything is open!)	→	SQAaaS	FAIRness metrics (objective quality assessment), metadata, standards, reproducibility, tracking of provenance

- Geo-INQUIRE provides Virtual Access (VA) and Trans-national Access (TA) to a portfolio of existing data, products, and services from many Research Infrastructures.



VA to the next generation of SaaS



- Several codes in volcanology:
 - Non HPC-oriented codes from other projects
 - HPC-oriented codes (OpenPDAC, ASHEE, FALL3D)
- Containerised applications (docker), code-related micro-services, CI/CD on EuroHPC systems including code documentation and testing.



TA to pioneer WaaS for probabilistic hazard analyses



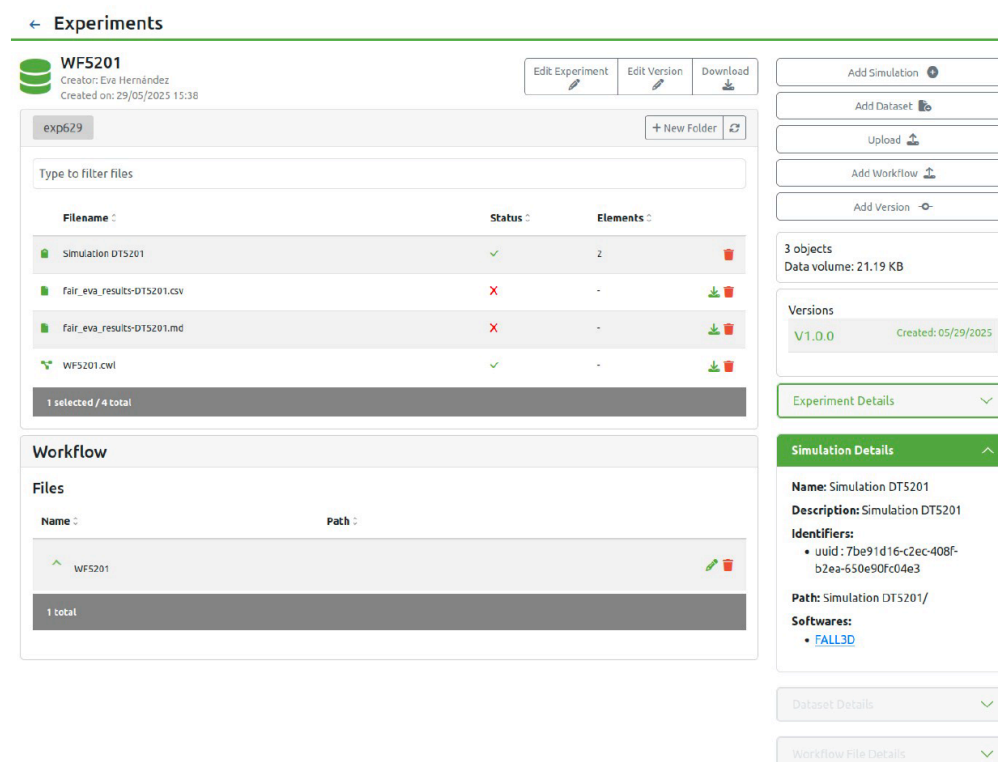
- FALL3D: long and short-term tephra Probabilistic Volcanic Hazard Assessment (PVHA)



Simulation Data Lake (SDL)

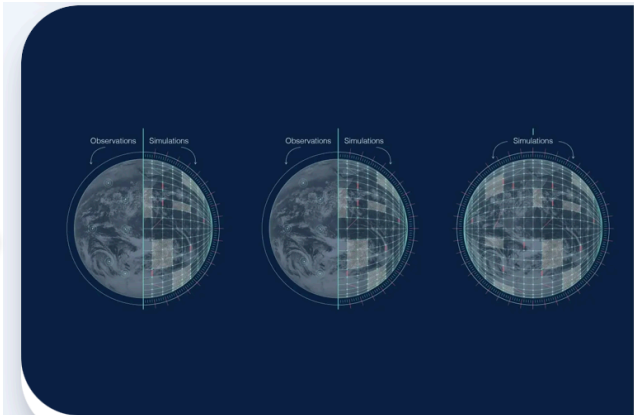


Platform developed by CINECA for storing and accessing simulation datasets to enhance data discoverability and reusability, open to the entire scientific community



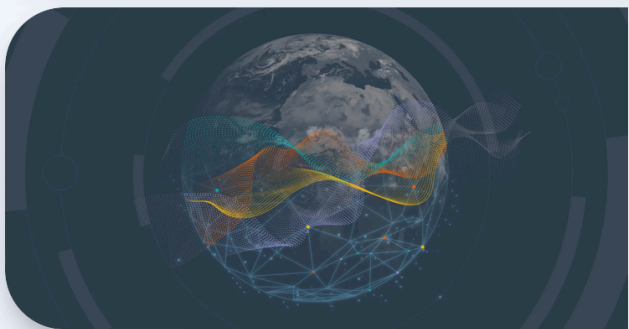
4. DestinE: a flagship initiative from the EU

- Implemented by 3 entities (ECMWF, EUMETSAT, ESA) entrusted by DG-CNECT.
- Evidence-based policy developments and actionable predictions.
- Users will run local-scale hazard assessments integrating DaaS, SaaS, WaaS and IaaS (cloud/HPC).



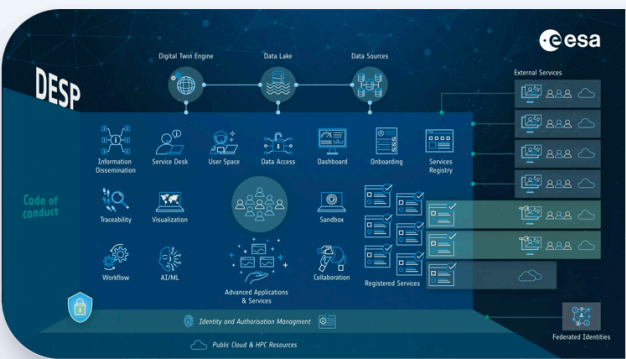
Digital Twins and Digital Twin Engine

DestinE is creating several digital replicas covering different aspects of the Earth system and based on state-of-the-art simulations and observations. ECMWF is implementing the Digital Twin Engine, the complex software and data services needed for Earth System digital replicas, as well as the first two digital twins; Climate Change Adaptation, which will provide multidecadal simulations, and the Weather-induced Extremes twin, with both high-resolution forecasts and on-demand simulations.



Data Lake

The data lake will bring together data from ESA, EUMETSAT, ECMWF as well as from Copernicus, and many other diverse sources, with new data from the Digital Twins. It will allow discovery and data access as well as big data processing in the cloud.



Core Service Platform

The platform will provide evidence-based decision-making tools, applications and services, based on an open, flexible, and secure cloud-based computing infrastructure.

Consists of	Simulations powered by extreme-scale HPC
Objective	Provide users with climate and weather information at the scales where impacts take place

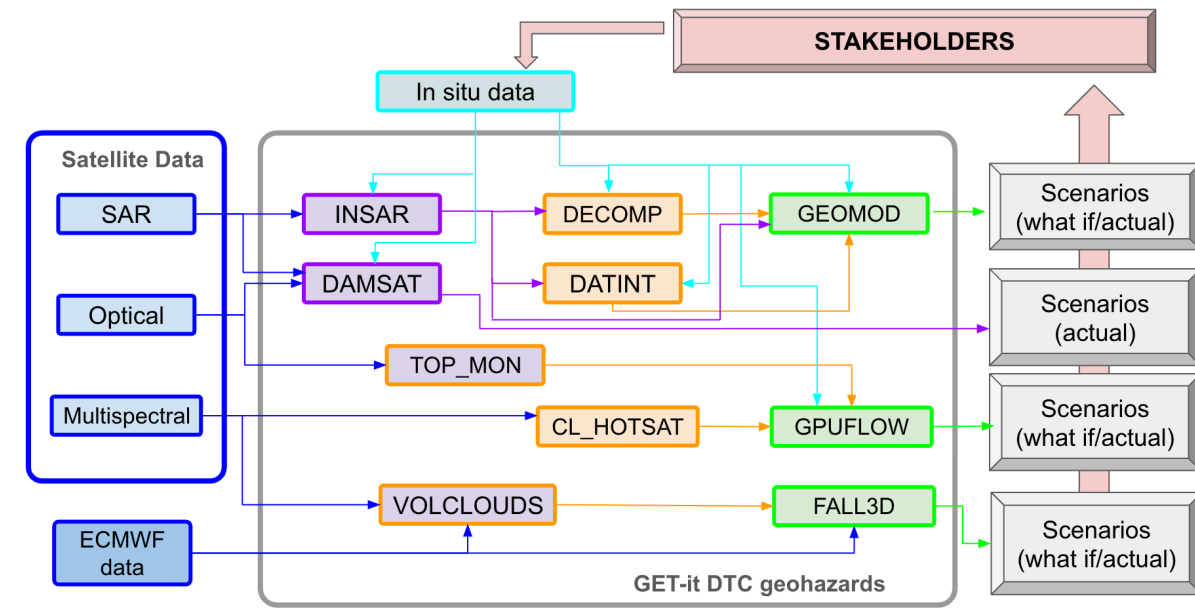
Consists of	Discovery and access to twins' data
Objective	Big-data processing services to compute close to data

Consists of	Cloud-based front-end for DestinE users
Objective	Provide applications, models and simulations for a better decision-making ("what if?")

Geohazards Early Digital Twin Component (GET-it)



- ESA project to test a Digital Twin Component (DTC) for geohazards (volcanoes, earthquakes) exploiting multi-sensor Earth Observation (EO) data and AI techniques.
- Deploy a roadmap for a fully operational DTC and its future integration in Destination Earth
- **Geohazards Exploitation Platform (GEP):**
 - Supports advanced geohazard monitoring and modelling WFs.
 - Will integrate GET-IT Geohazards DTC modules



Volcanic dispersal concept:

- Workflow to generate quantitative forecasts of volcanic ash/SO₂ clouds from numerical models by assimilating near real-time geostationary satellite data.

Products:

- **Quantitative volcanic ash (QVA)** concentration information including vertical column mass, concentration at flight levels, and layer-averaged concentration.
- The products provide information about airspace areas prone to be contaminated by hazardous concentrations at cruise Flight Level with resolution between 1 and 10 km and a temporal frequency of 1 h, approximately.

Users:

- Volcanic Ash Advisory Centers (VAACs), airports, aviation service providers, airlines.



Conclusions

- Modelling strategies for short and long-term volcanic dispersal are actually end members of a continuum.
- Traditional methodologies are evolving rapidly (high risk of volcanological community gap).
- Booting of HPC, digital twins, AI and adoption of consolidated software engineering technologies.

Coming soon (5-10 years ahead)...

- Uptake of all these emerging tendencies (entails a strong IT / multidisciplinary component, our community needs training!).
- The prominent role of Destination Earth and other federated infrastructures (e.g. “EPOS 2.0”).
- The ubiquitous role of AI: foundation models and LLM-enabled agentic AI systems present a transformative opportunity to advance geohazard impact assessment.

Thank you!

Murakoze!



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