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Center of Excellence for Exascale in Solid Earth

A computational model for atmospheric transport and deposition of tephra, dust, SO_2 and radionuclides

A. Folch (1), L. Mingari (1), A. Prata (1), G. Macedonio (2), A. Costa (3)

(1) Barcelona Supercomputing Center, Barcelona, Spain
(2) Istituto Nazionale di Geofisica e Vulcanologia, Napoli, Italy
(3) Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy

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The FALL3D model

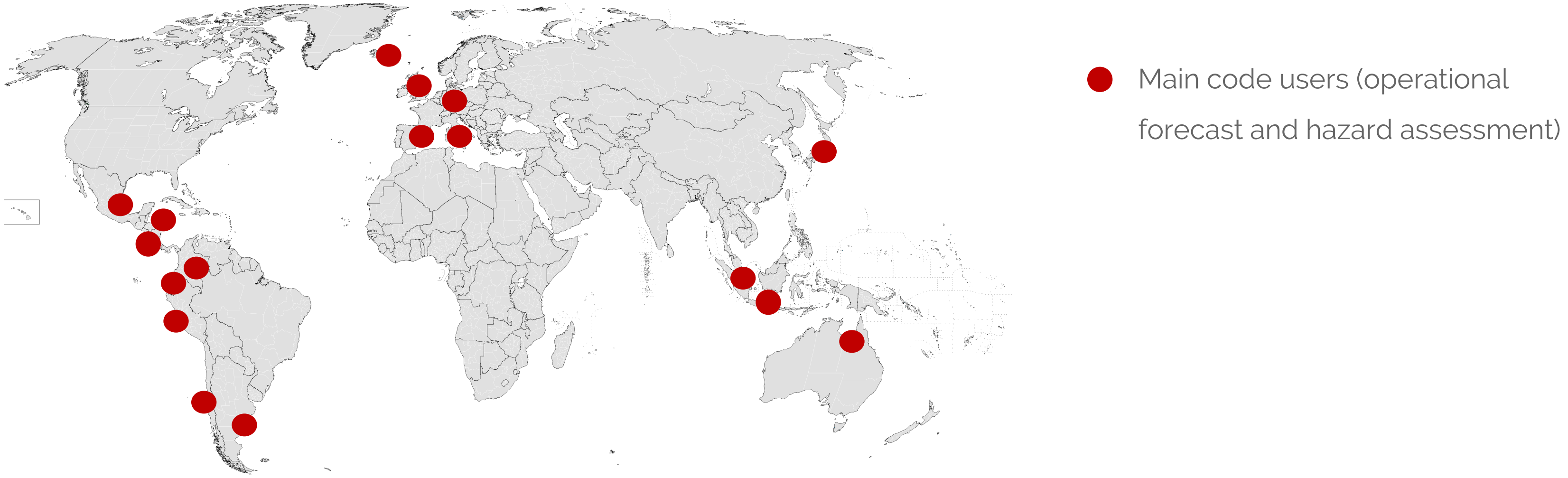
- Open-source off-line Eulerian model for atmospheric passive transport and deposition of particles and aerosols co-developed by BSC - INGV
- Based on the so-called Advection-Diffusion-Sedimentation (ADS) equation (1 equation per particle bin)
- Over 70+ publications on model verification and applications
- Long history record (almost 2 decades):

code version	year	Relevant milestone
1.0	2003	First version release in F77 at EGU2004 meeting (Costa and Macedonio, 2004)
2.0	2004	Coupling with BPT models for the source term
3.0	2005	Algorithmic improvements, Lax-Wendroff scheme (Costa et al., 2006)
5.0	2007	Code parallelization (MPI) and rewriting to F90 (Folch et al., 2009)
...	2008-2018	...
8.0	2020	**New version release with substantial physics, algorithmic and code performance improvements. Developed in the frame of the ChEESE Center of Excellence** (*)

(*) The Center of Excellence for Exascale in Solid Earth (ChEESE) is preparing 10 European flagship codes and related workflows for the upcoming Exascale computers (www.cheese-coe.eu)

The FALL3D model

- Model used for different purposes
  - Operational forecast
  - Hazard assessment (e.g. tephra fallout hazard maps, maps for concentration at FLs, etc.)
  - Reconstruction and characterization of past events
- Has an ever-growing community of users worldwide including Institutions with operational forecast mandates



What's new in FALL3D-8.0?

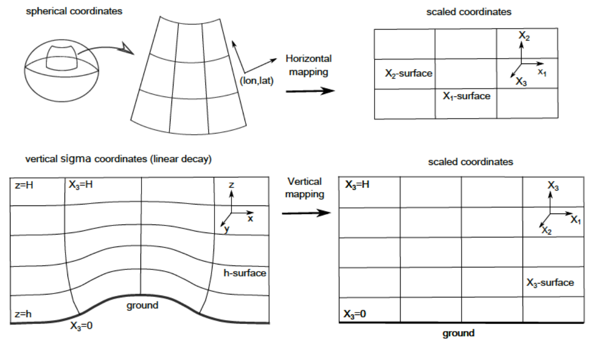
In terms of model physics

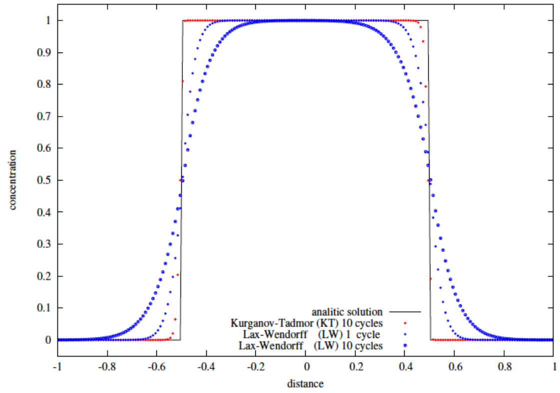
- Generalized to species different from volcanic tephra:
  - Other types of particles (e.g. mineral dust)
  - Aerosols (e.g. SO_2)
  - Radionuclides (including radioactive decay)
- Data insertion from satellite retrievals (preliminary step towards model data assimilation cycles)
- Updated meteorological drivers (e.g. ERA-5)
- Several classes (bins) of particle aggregates
- Periodic boundary conditions (regional from global domains)
- Updated physical parameterizations for source terms

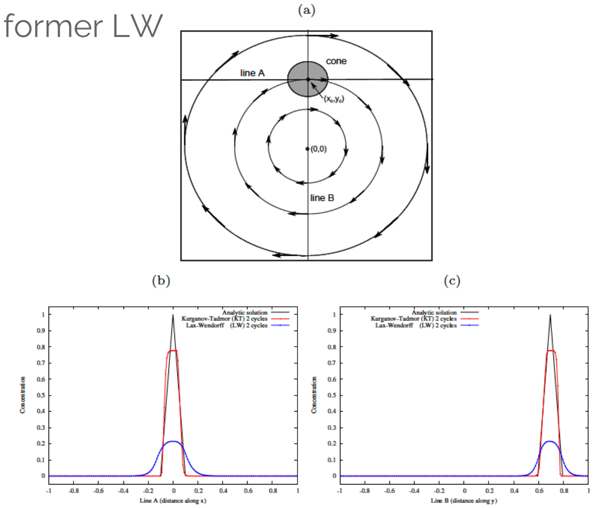
What's new in FALL3D-8.0?

In terms of model algorithmic

- New projections and vertical mappings, including a vertical σ-coordinate to capture better terrain effects
- Solving strategy:
  - Runge-Kutta 4th-order in time explicit scheme
  - High-resolution central-upwind scheme (Kurganov-Tadmor) replacing the former LW





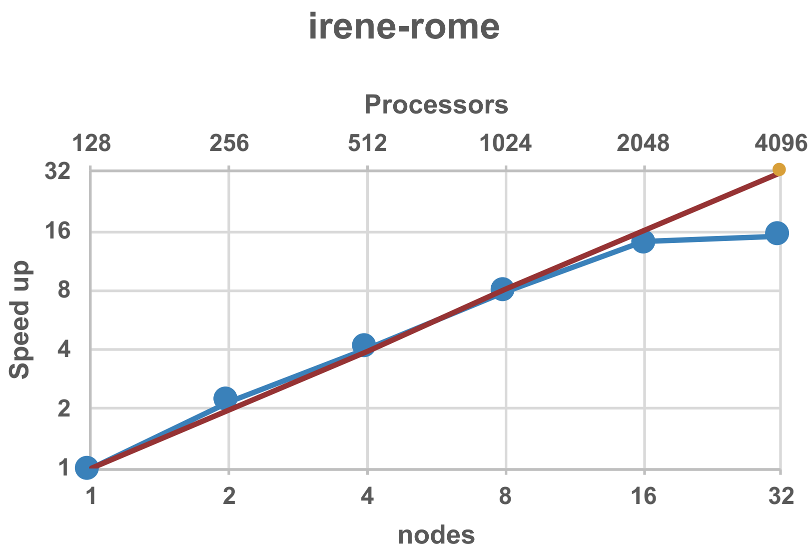


What’s new in FALL3D-8.0?

In terms of code performance

- New parallelization strategy (on domain and bins)
- More efficient memory management exists to exploit contiguous cache memory positions
- Parallel model I/O using netCDF
- Parallel model pre-process
- A hierarchy of MPI communicators for ensemble runs
- Open-MP pragmas at some critical code regions

- **Good parallel efficiency up to several thousands of processors**
- With respect to previous versions, the speedup increases with the number of cores up to factor 4.3

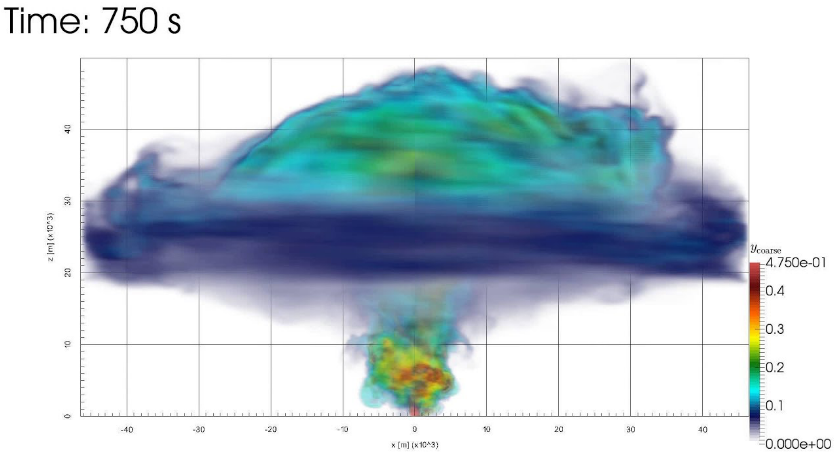


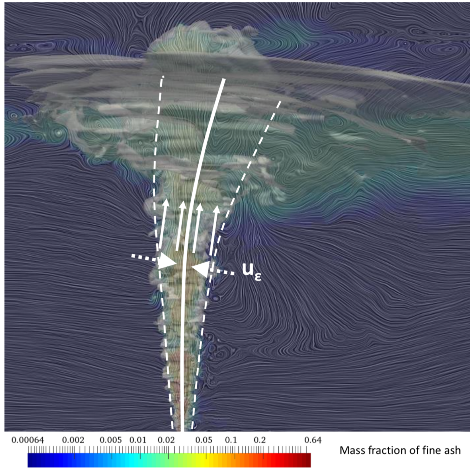
Strong scalability analysis (time to solution) at irene-rome supercomputer

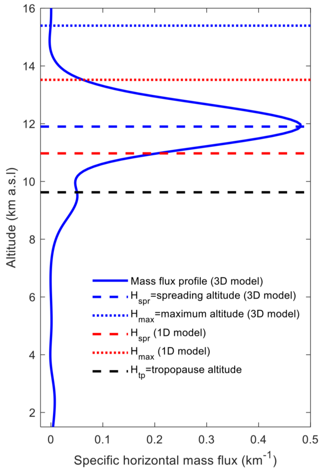
FALL3D in ChEESE Pilot Demonstrators (PDs)

PD3. High-resolution volcanic plume simulation

- Coupling between ASHEE (LES plume model) and FALL3D to provide more realistic representation of the volcano source term thereby reducing epistemic uncertainty
- Application to Calbuco (Chile) and Vesuvius eruption scenarios



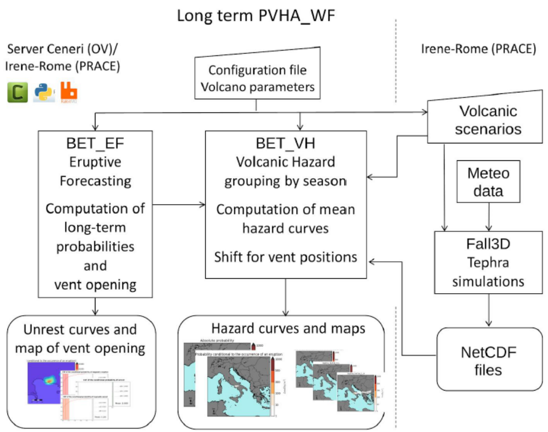


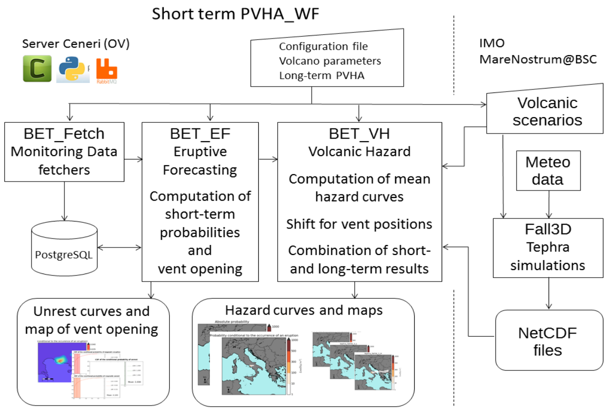


FALL3D in ChEESE Pilot Demonstrators (PDs)

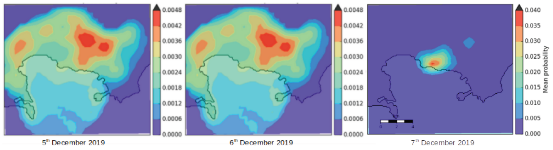
PD6. Probabilistic Volcanic Hazard Assessment (PVHA)

- Probability and hazard maps, with uncertainty, for tephra fallout at ground and airborne ash concentration and time-persistence at different flight levels exploring the natural variability in ESPs and wind conditions
- Full scenario variability range, on regional domains at high-resolution (~2 km)
- Application to Campi Flegrei (Italy) and Jan Mayen (Norway) volcanoes with Italian and Icelandic Civil Protections

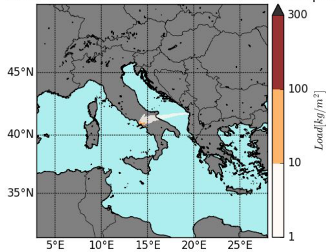




Vent opening maps, conditional to eruption occurrence



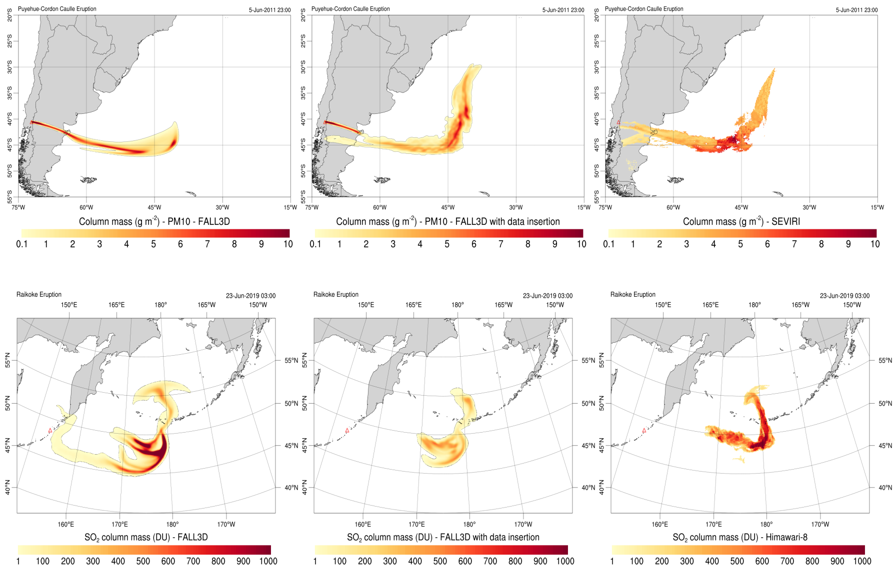
Tephra load with an exceedance probability of 5% in 00-48h conditional to the occurrence of an eruption



FALL3D in ChEESE Pilot Demonstrators (PDs)

PD12. High-resolution ash dispersal forecast

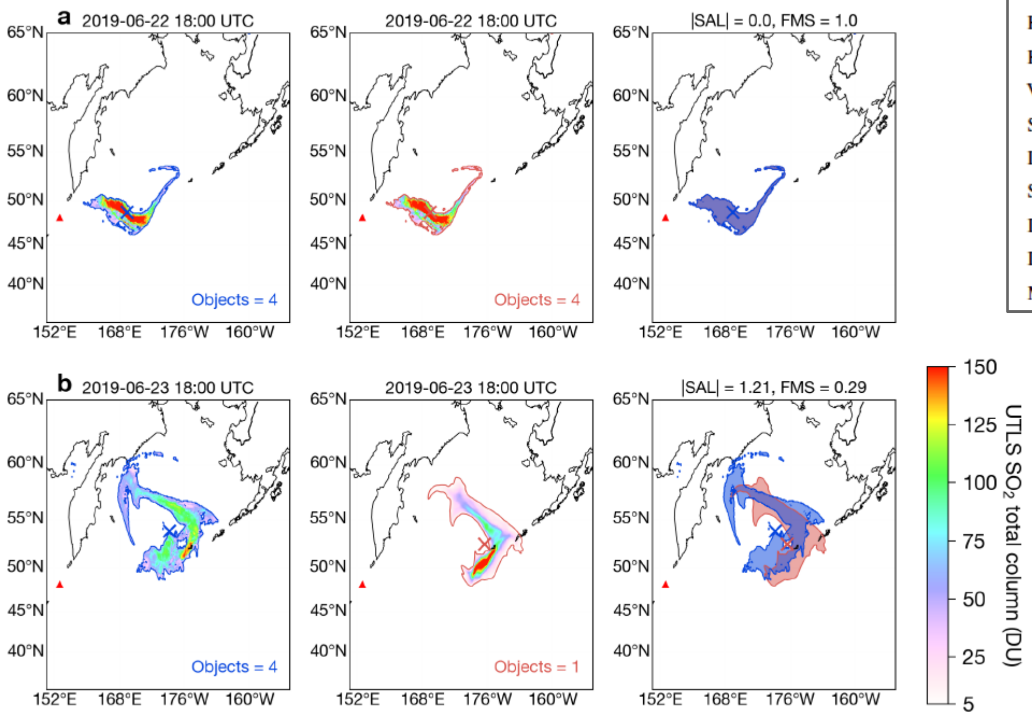
- Ensemble-based data assimilation system (workflow) combining the FALL3D dispersal model with high-resolution geostationary satellite retrievals (*)
- A high spatial model resolution on a continental scale (4 km horizontally for a domain including continental Europe and Iceland as opposed to the current 40 km horizontal resolution).
- Future service on tier-0 and on local tier-1/tier-2 machines



(*) Data assimilation not available in v8.0

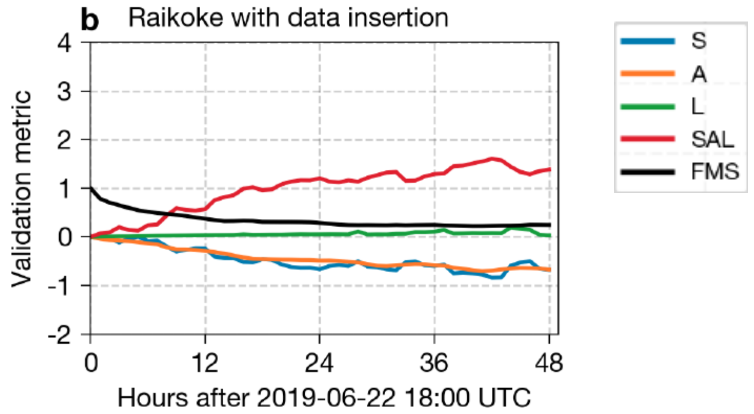
Validation example 1 : the 2019 Raikoke SO_2 cloud

Observation | Model | Comparison



Start date	2019-06-22
Start time	18:00 UTC
Run period	48 h
Resolution (hor.)	0.1°
Vertical levels	80
Species	SO_2
Data insertion	Yes
Source type	No source
Initial col. height	13.5 km
Initial col. thickness	2.5 km
Meteo. driver	GFS

Comparison with Himawari-8 SO2 satellite retrievals using SAL and FMS metrics



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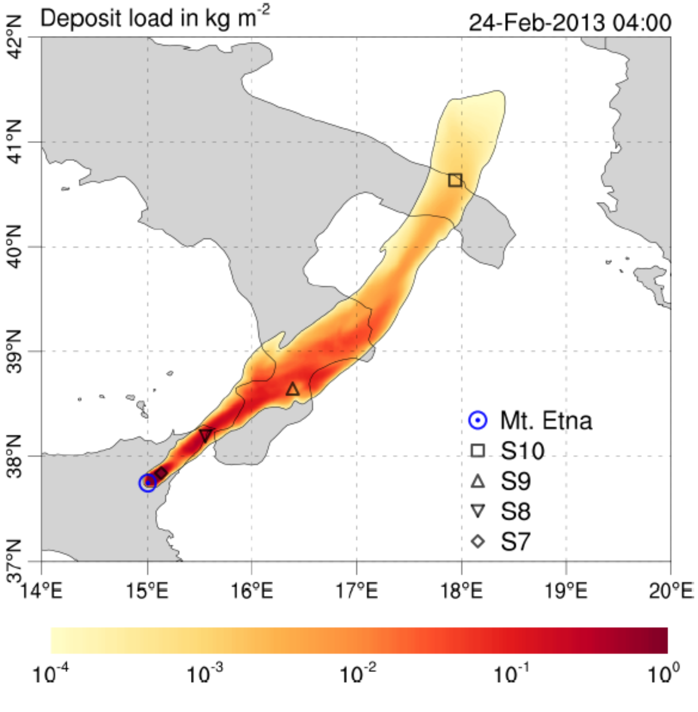
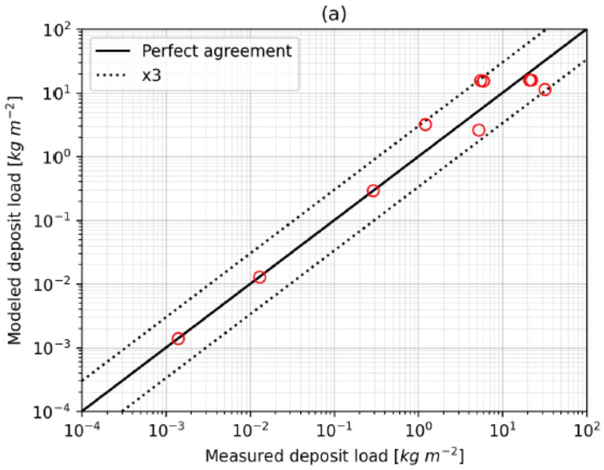
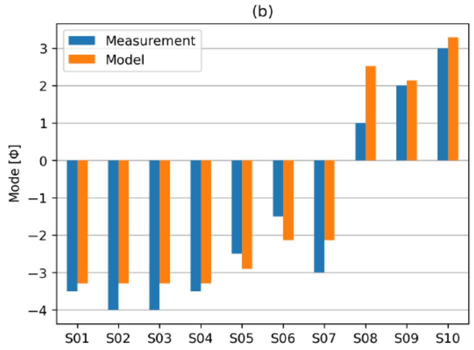
Validation example 2 : the 2013 Etna tephra deposit



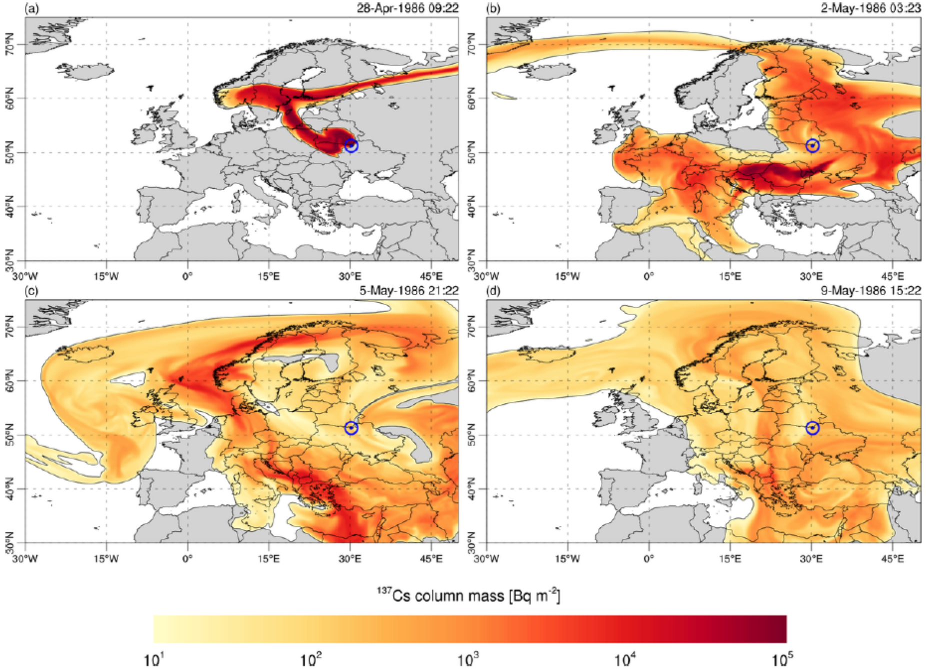
Start date	2013-02-23
Start time	18:00 UTC
Run period	10 h
Resolution (hor.)	0.015°
Vertical levels	60
Species	Tephra
Data insertion	No
Source type	Top-hat
Initial col. height	8.7 km
Initial col. thickness	3.5 km
Meteo. driver	WRF-ARW



Comparison with ground measurements at 10 locations of deposit thickness and particle grain size distribution (mode)

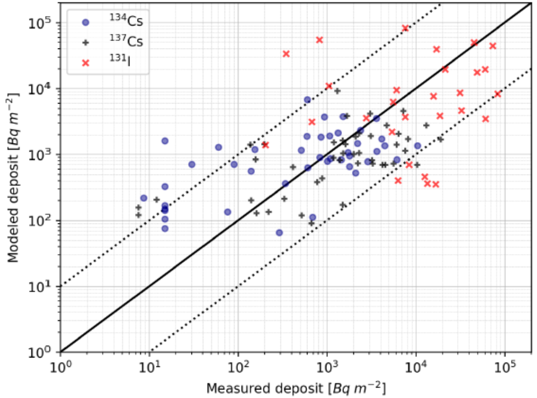


Validation example 3 : the 1986 Chernobyl accident



Start date	1986-04-25
Start time	00:00 UTC
Run period	384 h
Resolution (hor.)	0.125°
Vertical levels	60
Species	Radionuclides
Data insertion	No
Source type	hybrid
Initial col. height	3.3. km
Initial col. thickness	-
Meteo. driver	ERA5

Comparison with ground measurements at 137 locations across Europe for 3 isotopes



On-going developments

version release	Novel feature
8.1	**Ensemble modelling** • Probabilistic and deterministic forecasts • Automatic ensemble member generation for source term and meteorological fields • Single job execution (all members in 1 run)
8.2	**Porting to accelerators** • OpenACC pragmas • Preliminary results on P9 GPU cluster (NVIDA V100) give a performance increase of 4x
8.3	**Data assimilation** • Ensemble Transform Kalman Filter (EnTKF) • Parallel Data Assimilation Framework (PDAF)

References

- Costa, A., Macedonio, G., and Folch, A.: A three-dimensional Eulerian model for transport and deposition of volcanic ashes, Earth and Planetary Science Letters, 241, 634 – 647,, 2006.
- Folch, A., Costa, A., and Macedonio, G.: FALL3D: A Computational Model for Transport and Deposition of Volcanic Ash, Comput. Geosci., 35, 1334–1342, 2009.
- Folch, A., Mingari, L., Gutierrez, N., Hanzich, M., Macedonio, G., and Costa, A.: FALL3D-8.0: a computational model for atmospheric transport and deposition of particles, aerosols and radionuclides – Part 1: Model physics and numerics, Geoscientific Model Development,13, 1431–1458, 2020.

FALL3D is available under the version 3 of the GNU General Public License (GPL) at GitLab:

https://gitlab.com/fall3d-distribution

Grazie !