EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2026
Project Title:	Exploring the potential of uncertainty quantification and machine learning techniques to forecast rare extreme events
Computer Project Account:	SPCRDENA
Principal Investigator(s):	Clea Lumina Denamiel
Affiliation:	Ruđer Bošković Institute
Name of ECMWF scientist(s) collaborating to the project (if applicable)	/
Start date of the project:	2024
Expected end date:	2026

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	20,000,000	29,797,178	30,000,000	200,000
Data storage capacity	(Gbytes)	50,000	50,000	50,000	5,000

Summary of project objectives

The forecast of rare events (e.g., Derechos, meteotsunamis, tsunamis) with traditional ensemble methods (if even possible) is extremely costly in terms of numerical resources and is reaching the limit of what state-of-the-art numerical models can simulate in forecast mode. Consequently, the question of whether the cost of (not) forecasting these events is acceptable (i.e., human casualties vs. modelling capabilities and efforts) can be raised. In this project, we propose to explore the potential of using uncertainty quantification (UQ) and machine learning (ML) techniques (e.g., surrogate models/emulators) for the forecast of rare extreme events and to leverage the costs and benefits of such an approach. Different surrogates/emulators will be combined and compared for 3 selected rare extreme events: Derechos in Corsica, acoustically driven planetary meteotsunami waves and tsunamis caused by landslides in Mayotte.

Summary of problems encountered

No technical problems were encountered. However, due to unexpected circumstances, the simulations of the Corsica event (including hindcast, forecast and creation of the emulator) have been slightly delayed this year and reschedule in the summer (which explain why nearly no resources have been used).

Summary of plans for the continuation of the project (10 lines max)

The Mayotte landslide-tsunami subtask is now finished and published. The acoustically driven planetary meteotsunami subtask is completed in terms of the use of the numerical resources and an article is in preparation (we expect to submit the draft before the end of summer). The Corsica Derecho subtask is now well-advanced, but the emulator is still to be built which is how the remaining resources will be used.

List of publications/reports from the project with complete references

Denamiel, C., Marboeuf, A., Mangeney, A., Le Friant, A., Peruzzetto, M., Lucas, A., Castro Díaz, M. J., and Fernández-Nieto, E.: Landslide-Tsurrogate v1.0: a computationally efficient framework for probabilistic tsunami hazard assessment applied to Mayotte (France), Geosci. Model Dev., 19, 3075–3107, https://doi.org/10.5194/gmd-19-3075-2026, 2026.

Denamiel, C., Marboeuf, A., Mangeney, A., Le Friant, A., Peruzzetto, M., Lucas, A., Castro Díaz, M. J., and Fernández-Nieto, E.: Towards digital-twin-enabled tsunami hazard assessment: Landslide-Tsurrogate v1.0, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-4898, https://doi.org/10.5194/egusphere-egu26-4898, 2026.

Denamiel, C., Esposti Ongaro, T., and Huan, X.: Silent Threat: Predicting Acoustic Meteotsunami Global Hazards, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-7820, https://doi.org/10.5194/egusphere-egu25-7820, 2025.

Denamiel, C.: cdenamiel/Volcano-Meteo-Tsurrogate: Volcano-Meteo-Tsurrogate v1.0 package (EPOS-ON). Zenodo. https://doi.org/10.5281/zenodo.17711733, 2026.

Denamiel, C.: Landslide-Tsurrogate (v1.0). Zenodo. https://doi.org/10.5281/zenodo.19386796, 2026.

Summary of results

1. Landslides in Mayotte

During the project, we implemented and shared Landslide-Tsurrogate v1.0 which is an open-source Python and MATLAB tool that helps scientists quickly estimate the tsunami hazards generated by submarine landslides.

Instead of running thousands of heavy deterministic numerical simulations, the software builds surrogate models that reproduce the main results with a fraction of the computational cost. The method relies on a mathematical approach called generalized polynomial chaos expansion, which efficiently explores how uncertain landslide parameters affect tsunami generation. Users can perform sensitivity analyses, identify the most influential parameters, and quantify the variability of possible outcomes.

The tool includes a Jupyter Notebook User Manual and interactive MATLAB and Jupyter Notebook interfaces, making it easy to understand the methodology, set up the surrogate simulations and visualize the results (the package can be downloaded here: https://zenodo.org/records/19386796).

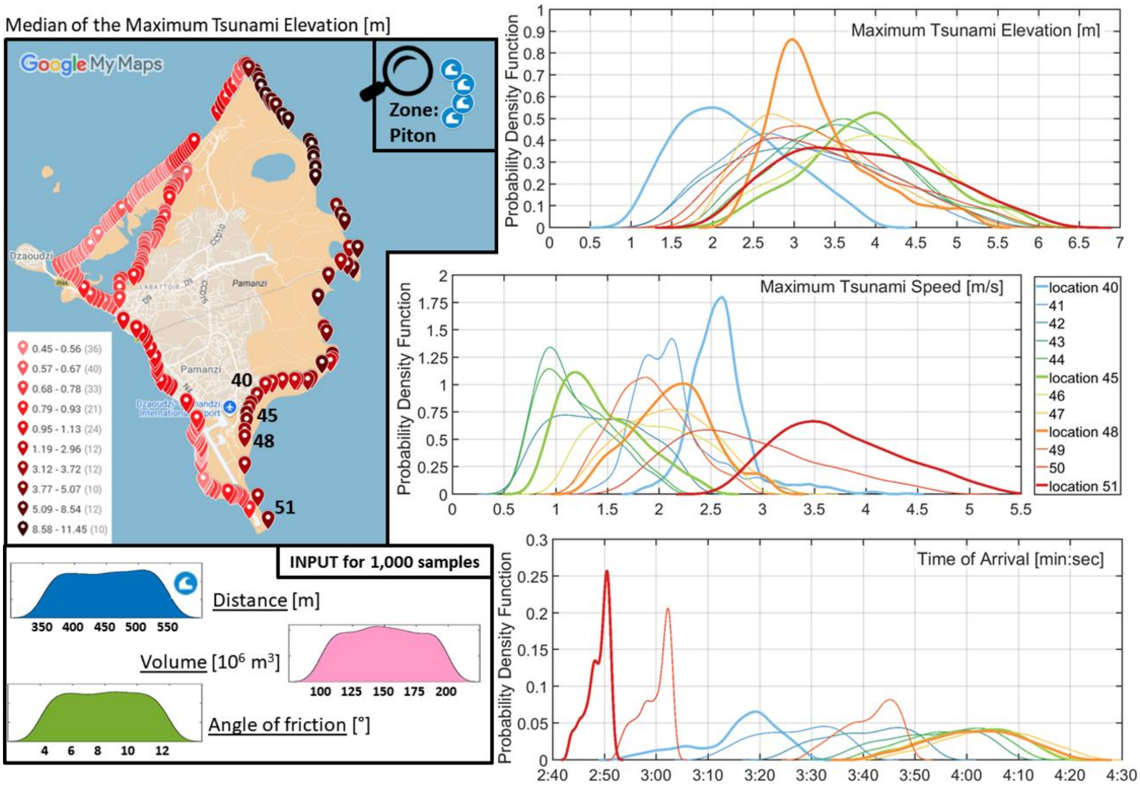


Figure 1. *Landslide Probabilistic Tsunami Forecast (PTF) derived from 1,000 conditions (or samples) for the Petite Terre Airport area and considering submarine landslides with volumes of V = 100-200 $10^6 m^3$ located at the tip of the Piton zone. The map represents the median of the maximum tsunami elevation distributions along the Petite Terre coastline while the probabilistic density distributions are displayed based on the surrogate models of maximum elevation, maximum speed and time of arrival located along the eastern coast of the airport area. Map data: c2026 Google.*

We demonstrated the Landslide-Tsurrogate v1.0 model's performance through a real-world test case involving five zones in Mayotte (France). For this application, the surrogate models achieve convergence with only 135 deterministic simulations per zone and produce probabilistic results in less than 2 s within the user-friendly interfaces used on a basic laptop, demonstrating the computational efficiency of the approach (Figs. 1 & 2).

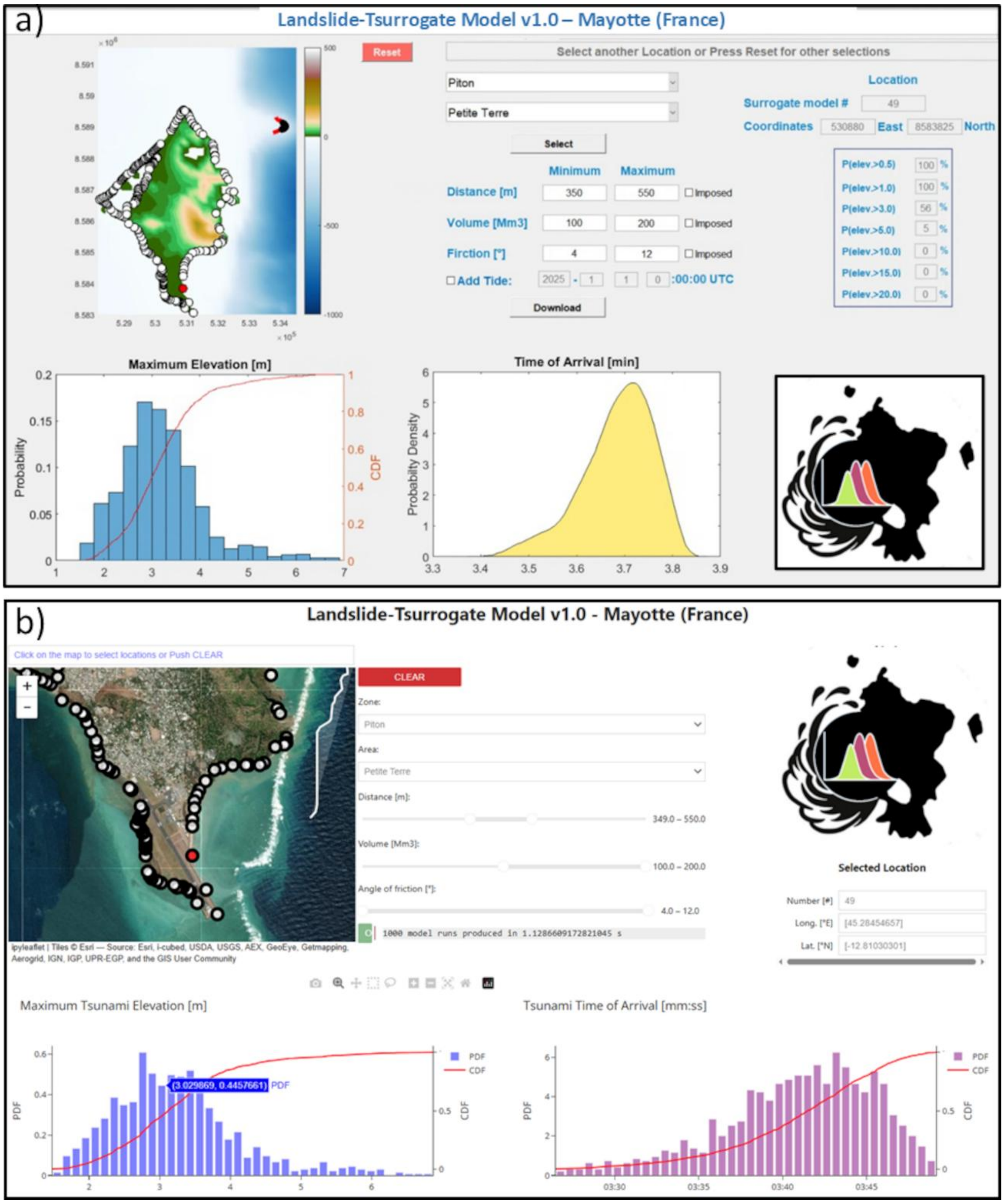


Figure 2. *Example of Landslide Probabilistic Tsunami Forecast (PTF) user-friendly interfaces for the Mayotte test case: (a) developed in MATLAB and distributed as program files for experts or as a Windows installer (.exe) for non-experts and (b) developed in Python and distributed as Jupyter Notebook for experts or deployed as a web application through Voila for non-experts. Map sources: Esri, i-cubed, USDA, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community.*

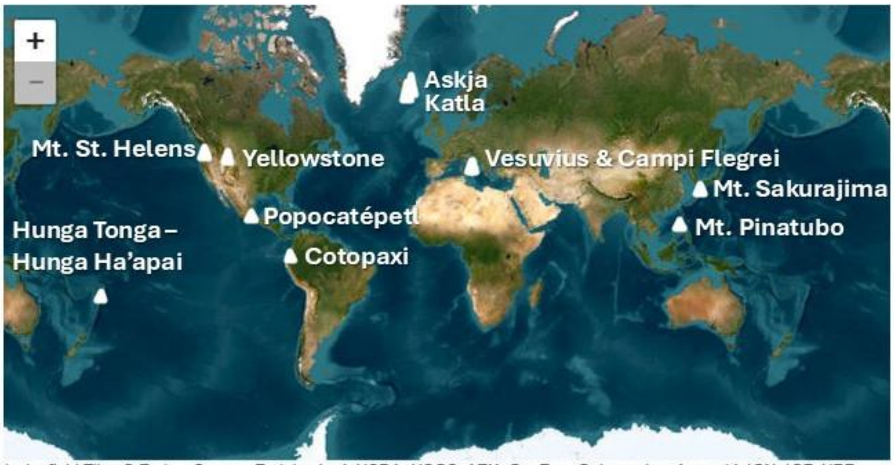
Beyond this example, the framework can be applied to any coastal region prone to submarine landslides. By combining modelling, statistical analysis, and user-friendly design, Landslide-Tsurrogate v1.0 enables faster and more transparent probabilistic tsunami hazard assessments.

2. Planetary meteotsunamis due to volcanic eruptions

During the project we also implemented and shared the Volcano-Meteo-Tsurrogate v1.0 which is an open-source Python tool that helps scientists quickly estimate planetary meteotsunami hazards generated by atmospheric Lamb waves after volcanic explosions.

As for Landslide-Tsurrogate v1.0, the software builds surrogate models at chosen coastal locations that reproduce the main results with a fraction of the computational cost. The method relies on a mathematical approach called generalized polynomial chaos expansion, which efficiently explores how uncertain atmospheric Lamb wave parameters affect meteotsunami generation.

Users can perform sensitivity analyses, identify the most influential parameters, and quantify the variability of possible outcomes. The tool includes a Jupyter Notebook User Manual and interactive Jupyter Notebook interface, making it easy to understand the methodology, set up the surrogate simulations and visualize the results (the package can be downloaded here: https://zenodo.org/records/17711733).



ipyleaflet | Tiles © Esri — Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community

Figure 3. *Geographical locations of the 11 studied volcanoes.*

The Volcano-Meteo-Tsurrogate v1.0 model's performance is demonstrated through a real-world test case involving 11 volcano locations (Fig. 3). For these applications, the surrogate models achieve convergence with only 385 deterministic simulations per volcano and produce probabilistic results in less than 2 seconds within the user-friendly interface used on a basic laptop (Fig. 4), demonstrating the computational efficiency of the approach.

Overall, Volcano-Meteo-Tsurrogate v1.0 demonstrates that surrogate modelling is a powerful tool for bridging the gap between high-fidelity deterministic meteotsunami simulations and practical probabilistic meteotsunami hazard assessment applications. The framework allows extensive uncertainty quantification, sensitivity analysis, and scenario exploration while maintaining computational efficiency.

Future work will focus on extending the surrogate model implementation to the inundation zone and the production of accurate inundation maps essential for risk assessment. In addition, Volcano-Meteo-Tsurrogate v1.0 will be expanded to incorporate alternative prior distributions of the stochastic variables beyond the uniform case, thereby enhancing its general applicability.

By enabling rapid yet reliable meteotsunami hazard assessment, Volcano-Meteo-Tsurrogate v1.0 represents a valuable step toward improved coastal risk management in meteotsunami-prone regions.

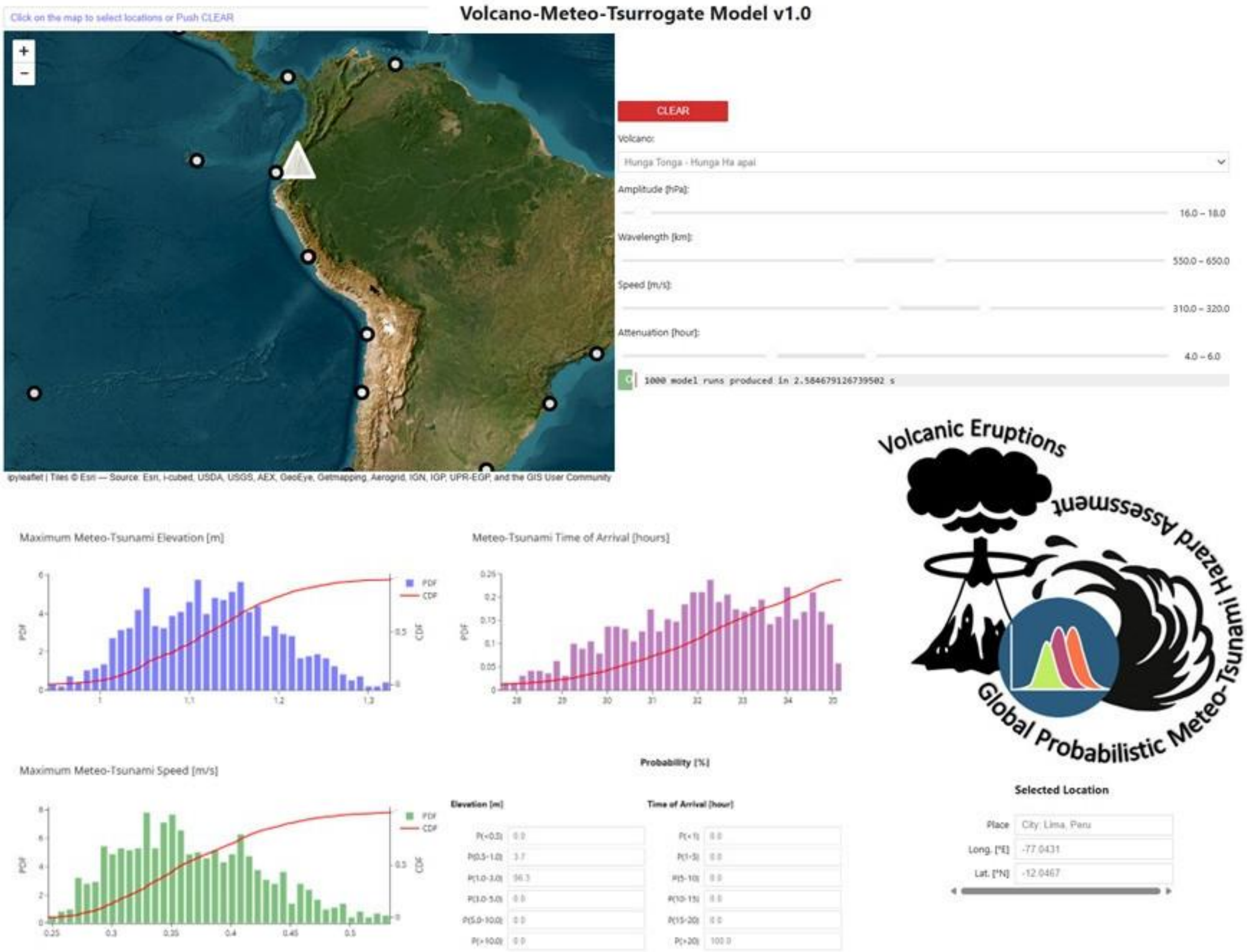


Figure 4. *User-friendly interface based on Jupyter Notebook, Widgets and Voilà. The presented example is for the 2022 Hunga Tonga-Hunga Ha'apai eruption that triggered a well-observed planetary meteotsunami.*

3. Derechos in the Ligurian and Tyrrhenian seas

The convective event that occurred over Corsica the 18 of August 2022 raised important questions regarding the, till now poorly explored, potential for meteotsunami generation and amplification along the Ligurian and Tyrrhenian coasts during derecho events. In a context where climate change may favour the development of highly organized and intense convective systems in the Mediterranean region, assessing the susceptibility of coastal areas to meteotsunami generation becomes increasingly relevant for coastal hazard mitigation and early warning strategies.

However, classical forecasts provided by meteorological services often fail to reproduce such mesoscale events and their associated meteotsunamis. Previously, we have demonstrated that the minimum modelling requirements necessary to realistically simulate and forecast meteotsunami events in the Adriatic region, including the need for kilometre-scale atmospheric forcing, high-frequency (minute-scale) air-pressure fields, and meter-scale ocean models capable of resolving coastal resonance processes. Generally, such modelling frameworks remain computationally expensive, making their application within real-time large ensemble or probabilistic forecasting systems particularly challenging.

In addition, we have already highlighted that accurately forecasting the intensity, trajectory, and spatial structure of convective disturbances capable of generating meteotsunamis remains elusive, especially for rapidly evolving mesoscale systems. These limitations show the need for alternative approaches allowing to rapidly explore a broad range of plausible atmospheric forcing scenarios while retaining the essential physical mechanisms governing meteotsunami generation and amplification as explored along the US coasts and already implemented in the Adriatic Sea.

During this project we thus are developing and implementing the Triggered Integrated Response to Regional Atmospheric Nonlinear Oscillations (TIRRANO) modelling system with the aim to assess and forecast meteotsunami hazards over the Ligurian and Tyrrhenian seas. TIRRANO (Fig. 5) is based on a highly modular approach and model setup—implemented and successfully tested in the Adriatic Sea—which coupled (1) a deterministic regional atmosphere-ocean module, (2) a deterministic high-frequency module and (3) a stochastic meteotsunami hazard module.

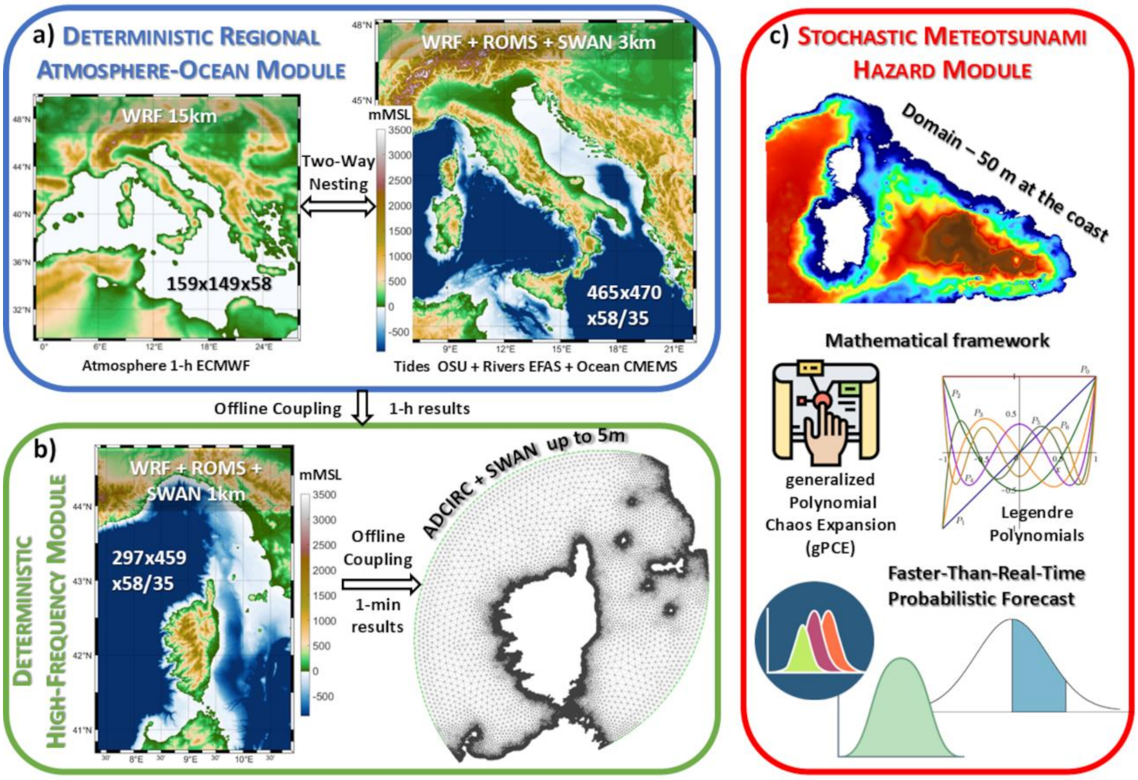


Figure 5. *Modules of the Triggered Integrated Response to Regional Atmospheric Nonlinear Oscillations (TIRRANO) modeling system. (a) deterministic regional atmosphere-ocean module, (b) deterministic high-frequency module, and (c) stochastic meteotsunami hazard module.*

In this project, we already have completed a process-oriented study of the 2022 derecho event using 11 virtual stations automatically selected along the simulated meteotsunami pathway (Fig. 6) where the strongest meteotsunami waves are simulated with the TIRRANO models are initiated and forced with reanalysis products. We found that four of these stations (4–7) are located along the coastline of the Gulf of Porto, where a 62-year-old man was reported missing during the 18 August 2022 derecho event and was subsequently found dead at sea. Although the exact cause of the accident remains unknown, the presence of several virtual stations in this area provides us an opportunity to examine whether the simulated meteotsunami activity could have contributed to hazardous sea conditions along this section of the Corsican coast.

Our analysis reveals the progressive development of the meteotsunami wave train as the atmospheric disturbance propagates across the basin (Fig. 6). The largest simulated waves occur along the coastline of the Gulf of Porto (Stations 2–5), where maximum wave heights reach 1.46 m and dominant periods range from approximately 4 to 8 min. Although no direct causal relationship can be established between the fatality and the simulated meteotsunami activity, the coincidence of the strongest simulated high-frequency sea-level oscillations with the affected area suggests that meteotsunamis may have contributed to hazardous coastal conditions during the event.

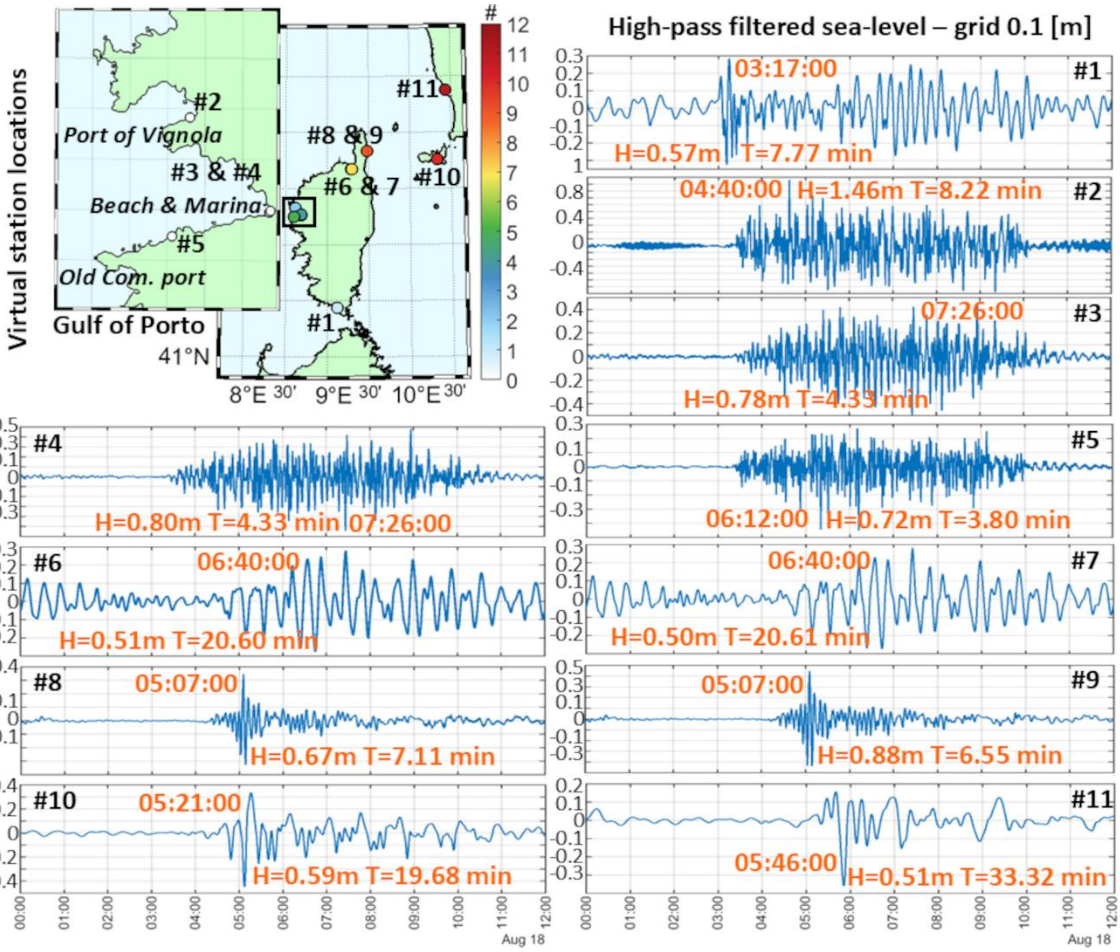


Figure 6. *Modules of the Triggered Integrated Response to Regional Atmospheric Nonlinear Oscillations (TIRRANO) modeling system. (a) deterministic regional atmosphere-ocean module, (b) deterministic high-frequency module, and (c) stochastic meteotsunami hazard module.*

In this study project we already demonstrated the capability of the TIRRANO modelling system to reproduce the atmospheric and oceanic processes leading to meteotsunami generation during the 18 August 2022 Corsica derecho event. However, the simulated atmospheric disturbance is spatially displaced with respect to the observations. Till now, we also identified the Gulf of Porto as a hotspot for the amplification of meteotsunamis during this event.

Consequently, we believe that these findings highlight the critical need to better understand and quantify meteotsunami hazards in the Ligurian and Tyrrhenian Seas. In particular, they provide strong motivation for developing probabilistic meteotsunami hazard assessments that combine high-resolution atmospheric modelling with coastal hydrodynamic simulations to identify regions most susceptible to these events. Such assessments are planned for the rest of the project, and we expect that they will represent an important step toward improving coastal risk management and the development of operational early-warning capabilities for meteotsunamis in the western Mediterranean.