REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation:	Italy
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Project Title:	Multi-Hazard climate change assessment with Digital Twins to support coastal resilience

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES X☐	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	100 M	30 M	
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	10,000	25,000	

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

EWC resources required for project year:		2027	2028	2029
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

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Extended abstract

All EMI R&D Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the EMI R&D Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous EMI R&D Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

Abstract

Coastal cities are increasingly exposed to climate change-related hazards, including coastal and riverine flooding, sea-level rise, and erosion. These processes often interact as compound events, requiring integrated multi-risk approaches to assess their impacts at the local scale. This research aims to conduct a multi-hazard analysis of current and future flood hazards in a coastal city under different climate scenarios. Downscaled climate data, including river discharge, waves, storm surge, tides, and sea-level rise projections, will be used to perform a large ensemble of high-resolution hydrodynamic simulations with a phase-resolving coastal model. The resulting dataset will support the development of a machine-learning surrogate model, enabling the rapid simulation of alternative what-if scenarios within a Digital Twin environment. This framework will make it possible to perform a comprehensive multi-risk analysis, assessing how these processes may co-occur and what compound impacts they may produce in the urbanized area.

Motivation

Coastal urban systems, which host more than 2 billion people worldwide, can be considered complex socio-environmental systems where natural processes, climate variability, and human activities interact across multiple spatial and temporal scales. Today, coastal cities are increasingly exposed to the adverse impacts of climate change, making them critical hotspots of natural risk (IPCC, 2023; Vitousek et al., 2017; Oppenheimer et al., 2019). These densely populated and economically vital regions are threatened by a range of hazards, including coastal and riverine flooding. Moreover, coastal erosion and sea-level rise (SLR) contribute to permanent land loss, infrastructure damage, and the weakening of natural defenses such as dunes and vegetated shorelines, thereby increasing flood risk (Oppenheimer et al., 2019; Vousdoukas et al., 2020; Defeo et al., 2021; van de Wal et al., 2024).

Hazards often co-occur and interact through shared drivers, such as climate change, urbanization, and altered hydrological regimes. This requires an integrated multi-hazard approach to accurately assess and manage compound and cascading effects (Laino et al., 2024). A multi-hazard perspective helps identify synergies and trade-offs among different hazards and supports more informed decision-making. Within this context, Nature-based Solutions (NbS) emerge as effective tools to simultaneously address erosion, flooding, water quality, and ecological restoration, while also providing co-benefits such as recreation, tourism, and improved urban livability (Gallina et al., 2020). High-resolution climate data, combined with innovative tools such as Digital Twins (DTs), can support multi-hazard assessments, scenario simulations, and the evaluation of NbS effectiveness within participatory and governance-oriented environments. These tools can therefore enhance climate adaptation and resilience at the local scale (Yu et al., 2024).

The main objective of this project is to conduct a multi-hazard analysis to assess riverine and coastal flooding through a quantitative approach, with particular attention to how these processes may co-occur and interact under both current and future climate scenarios. Within this framework marine and fluvial processes are considered the primary flood-generating drivers, and may also occur simultaneously as compound events. Coastal flooding is typically driven by storm surge, high significant wave heights, and tidal conditions, all of which can be exacerbated by long-term sea-level rise associated with climate change. River flooding, on the other hand, is mainly caused by intense or prolonged precipitation leading to high river discharge, often combined with elevated downstream water levels in estuarine zones. In coastal cities, these processes are not fully independent: marine conditions can affect river outflow by acting as a hydrodynamic boundary condition, while river discharge can influence coastal water levels. This interaction is particularly critical in areas where the coupling between fluvial and marine dynamics can amplify flood intensity.

To assess flood hazard at the local scale, a large number of physics-based hydrodynamic simulations should be performed in order to explore the possible configurations and interactions among the different hazard drivers. Each simulated configuration would then be associated with a return period or occurrence probability based on the probabilistic analysis of the forcing variables. In particular, downscaled climate data on river discharge, wave dynamics, and storm surge will be required, including both hindcast datasets and future climate projections. These forcing data will be mainly derived from previous projects such as H2020 SCORE and Interreg-MARITTIMO AMIS:

- The H2020 SCORE project provides downscaled datasets from WW3 for waves, SHYFEM for storm surge, and LISFLOOD for river discharge, including hindcast data and projections up to 2100 (https://score-eu-project.eu/).
- The Interreg-MARITTIMO AMIS project provides additional downscaled WW3 wave data and SHYFEM storm-surge data, supporting the definition of marine boundary conditions for coastal flood scenarios (https://interreg-marittimo.eu/web/amis).

In addition to these modelling datasets, the Interreg-MARITTIMO MAREGOT project (https://interreg-maritime.eu/web/maregot) represents an important methodological reference for the use of XBeach in coastal hazard assessment. Within MAREGOT, XBeach was applied to simulate coastal hydrodynamic and morphodynamic processes, with particular attention to wave runup, coastal flooding, and erosion dynamics. The project also highlighted the relevance of coastal video-monitoring systems and webcam-derived observations for model calibration and validation (Carpi et al., 2019). This approach is particularly relevant for the present research, where webcam data and local observations will be used to support the calibration of the NH-XBeach model and improve the reliability of simulated flood extent, runup, and nearshore hydrodynamics.

A compound-event statistical analysis will be performed to define physically and probabilistically consistent combinations of flood-generating drivers for the hydrodynamic simulations. After identifying independent extreme events and possible temporal lags between marine and fluvial processes, the marginal distribution of each variable will be modelled and the dependence among key drivers, such as river discharge, storm surge, wave conditions, and still water levels, will be assessed through bivariate analysis and copula-based approaches (Nicolae Lerma et al., 2018). This will allow joint exceedance probabilities and return periods to be estimated, supporting the generation of statistically consistent present-day and future compound flood scenarios within the broader multi-hazard framework.

The statistically defined compound scenarios will then be combined with tidal levels and sea-level rise projections and used to perform a large ensemble of local-scale hydrodynamic simulations in the coastal area, using a phase-resolving wave model such as NH-XBeach (documentation: https://xbeach.readthedocs.io/en/latest/). The model setup, calibration, and validation will build on previous experiences with XBeach-based coastal hazard assessment, including the use of coastal video-monitoring and webcam observations to compare simulated and observed shoreline dynamics, runup patterns, and flood extent. This type of model is able to simulate a wide range of coastal and nearshore processes, including wave propagation and transformation, nonlinear wave-current interactions, wave-induced nearshore circulation, wave breaking, runup, and sediment transport. The model can also account for external drivers such as storm surge, tides, sea-level rise, and river discharge at the river mouth (de Beer et al., 2020; Roelvink et al., 2009).

Such simulations require substantial computational resources in terms of both processing time and data storage. However, the resulting large dataset of hydrodynamic simulations could be used to train a machine learning algorithm acting as a surrogate model. This surrogate model would enable very fast simulations of additional possible events and, most importantly, could be integrated into a Digital Twin with two main purposes:

1. To provide an informative dataset of future climate scenarios, each associated with an occurrence probability;
2. To allow users to create customizable what-if scenarios, whose results could be generated in real time through the surrogate model. This tool would be particularly valuable to evaluate different adaptation strategies for sustainable coastal management, while also identifying potential trade-offs and conflicts among alternative solutions.

Despite recent advances in coastal flood modelling and climate-risk assessment, local-scale analyses often still consider coastal and riverine flooding separately, neglecting the nonlinear interactions that may arise when marine and fluvial drivers occur simultaneously. Moreover, the high computational cost of physics-based hydrodynamic models limits their systematic application to large ensembles of current and future scenarios. This creates a methodological gap between the need for detailed, process-based flood simulations and the operational demand for fast, interactive tools capable of supporting planning and decision-making. This project addresses this gap by combining high-resolution numerical modelling, probabilistic multi-hazard analysis, machine-learning-based surrogate modelling, and Digital Twin technologies.

In conclusion, this research aims to develop an integrated modelling framework for the local-scale assessment of coastal and riverine flood hazards in coastal urban areas under current and future climate conditions. By combining downscaled climate projections, sea-level rise scenarios, tidal information, local observations, and high-resolution hydrodynamic simulations calibrated through available monitoring data, the project will investigate how multiple flood-generating processes may co-occur, interact, and amplify impacts across the urbanized area. The resulting simulation database will provide the basis for training a machine-learning surrogate model, enabling rapid exploration of additional probabilistic and user-defined what-if scenarios within a Digital Twin environment. This framework is expected to support comprehensive multi-hazard analysis, improve the understanding of compound flood dynamics, and provide a decision-support tool for evaluating adaptation strategies, including Nature-based Solutions, in the context of sustainable coastal management.

Workplan

Workplan and resource distribution

The project is planned as a two-year activity, with the largest share of the computational allocation requested in the first year. This front-loaded distribution is intentional: the first project year will be used not only for porting, benchmarking and workflow consolidation, but also for the production of most of the NH-XBeach ensemble needed to train the Digital Twin surrogate model. The second year will focus on completion runs, reruns of unstable cases, post-processing, uncertainty analysis and integration of the reduced dataset into the machine-learning workflow.

Year 1 - 2027: model porting, scaling and main production

- Model porting and benchmarking on ECMWF Atos. The NH-XBeach configuration will be compiled and tested on the Atos HPCF using the available GNU/Intel/AOCC compiler and MPI environments. Benchmark tests will be performed on 56, 64, 128 and, if justified, 256 physical cores to identify the best compromise between wall-clock time, SBU efficiency and I/O performance.
- Definition of the probabilistic scenario matrix. Downscaled river discharge, waves, storm surge, tide and sea-level rise scenarios will be combined into a consistent ensemble design. The target ensemble size is 1000 high-resolution simulations, sampling the joint variability of storm forcing, water levels and discharges.
- Main NH-XBeach production ensemble. Once the optimal production configuration has been selected, approximately 700-750 simulations will be run during the first year, depending on the final scaling performance and restart requirements. This early production phase is necessary to generate a sufficiently large and diverse training dataset for the machine-learning surrogate model while the full scientific team is actively involved in the project.
- First diagnostic extraction. For each run, full raw outputs will be reduced to physically interpretable indicators, including maximum water level, runup, inundation extent, velocity-related hazard metrics and boundary-condition metadata. This will limit the amount of data requiring long-term archive storage.

Year 2 - 2028: completion, validation, post-processing and Digital Twin integration

- Completion of the ensemble. The remaining approximately 200-300 simulations will be completed, including reruns of failed or numerically unstable cases and additional simulations required by the final scaling and validation results.
- Validation and uncertainty analysis. The ensemble results will be analysed to quantify the sensitivity of local-scale flooding and erosion indicators to marine forcing, fluvial discharge, sea-level rise scenarios and initial morphology.
- Surrogate model training. The reduced hydrodynamic database will be used to train and validate a machine-learning surrogate model capable of rapidly emulating the NH-XBeach response for alternative what-if scenarios.
- Digital Twin demonstrator and adaptation assessment. The surrogate model will be integrated into the Digital Twin workflow to support rapid testing of what-if scenarios and adaptation measures.

Technical characteristics of the code

The numerical engine is NH-XBeach, i.e. the non-hydrostatic, phase-resolving configuration of XBeach. This configuration is required because the project focuses on local-scale compound flood hazard, where individual-wave transformation, nonlinear wave-current interaction, wave breaking, runup, overwash and coastal inundation may control the maximum water levels and the inland extent of flooding. The code is parallelised with MPI and will be run as a distributed-memory application on the ECMWF Atos HPCF. The Atos compute nodes are based on AMD EPYC Rome processors with 128 physical cores per compute node, 256 GiB memory per compute node and HDR InfiniBand interconnect; therefore, the production setup will be selected after testing both sub-node and full-node configurations. The present benchmark uses a 1490 x 1875 computational grid, corresponding to 2,793,750 computational cells. A representative non-hydrostatic run using 56 MPI processes required 20,000 s of elapsed time to simulate 1 h of physical time. This corresponds to 5.56 wall-clock hours and 311 core-hours per simulated hour. A 24 h storm simulation therefore requires approximately 133 wall-clock hours on 56 cores, or 7,467 core-hours per simulation. Since the current 56-core benchmark indicates that a full 24 h storm simulation would exceed the standard 2-day wall-clock limit, production runs will either be split into restart segments or executed on a higher core count, depending on the outcome of the scaling tests.

Justification of the requested computing resources

The production ensemble consists of 1000 NH-XBeach simulations. Using the benchmark above, the production cost is estimated as 7,467 core-hours per simulation x 1000 simulations = 7.47 million core-hours. According to the current ECMWF HPC2020 accounting formula, SBU charging is based on the elapsed time and the number of allocated physical cores; the 2026 reference value is approximately 17.06 SBU for a serial job using 1 h of elapsed time. This gives an indicative production cost of about 127 million SBU. A total allocation of 130 million SBU is requested to include production simulations, scaling tests, restarts, reruns of failed cases, sensitivity tests, workflow development and post-processing.

The allocation is intentionally front-loaded: 100 million SBU are requested for 2027 and 30 million SBU for 2028. This distribution reflects the need to complete most of the computationally intensive ensemble during the first year, when the modelling workflow, scenario matrix and scientific supervision are being consolidated. The second-year allocation is reserved for completion runs, reruns, uncertainty analysis and post-processing.

Each 24 h simulation will write three full-domain variables every 120 s (the water level z_s, the u and v horizzontal velocities), corresponding to 720 output times per simulation. For the 1490 x 1875 grid, this corresponds to approximately 24 GB per simulation in single precision or 48 GB per simulation in double precision before compression. The raw temporary output for the full ensemble is therefore expected to be of the order of 25-50 TB. Only reduced diagnostics and selected fields will be archived permanently; the requested accumulated archive storage is 10 TB in 2027 and 15 TB in 2028, for a cumulated value of 25 TB in the second year.

The requested resources are therefore necessary to generate a statistically meaningful ensemble of local-scale, phase-resolving simulations. A small deterministic set of simulations would not be sufficient to sample the joint variability of marine forcing, fluvial discharge, sea-level rise and morphology, nor to train a robust surrogate model for the Digital Twin framework.

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