REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation:	Italy
Principal Investigator[1]:	Paolo Stocchi
Affiliation:	The Institute of Atmospheric Sciences and Climate-National Research Council (ISAC-CNR)
Address:	Via Pietro Gobetti, 101, 40129 Bologna BO
Other researchers:	Dr. Giuseppe Zappa (ISAC-CNR Bologna), Dr.ssa Susanna Corti (ISAC-CNR Bologna), Dr. Valerio Lembo (ISAC-CNR Roma)
Project Title:	**Advanced pseudo-global warming simulations for attribution of Mediterranean weather extremes**

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]	**3 million**	**3 million**	**3 million**
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	**15 TB**	**15 TB**	**15 TB**

[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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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).

Extended abstract

Mediterranean weather extremes, including heavy precipitation events, floods, windstorms and heatwaves, are expected to intensify under anthropogenic climate change, posing increasing challenges for climate adaptation and risk management. However, quantifying the contribution of climate change to individual high-impact events remains difficult, particularly in regions characterized by complex topography, strong land–sea interactions and intense mesoscale processes.

MOSAIC-MED (MOLOCH Storyline Attribution of Mediterranean Extreme Events) aims to develop a novel convection-permitting framework for the attribution of Mediterranean weather extremes by combining pseudo-global-warming (PGW) experiments, climate storylines from Destination Earth and high-resolution numerical simulations with the MOLOCH atmospheric model. The proposed methodology will generate counterfactual realizations of selected extreme events through the application of thermodynamic climate perturbations derived from circulation-constrained Destination Earth storylines to ERA5 reanalysis data. Both factual and counterfactual simulations will be dynamically downscaled from ERA5 to convection-permitting resolution (~2 km) using MOLOCH with spectral nudging, ensuring consistency with the large-scale atmospheric circulation while explicitly resolving mesoscale and convective processes.

To improve the robustness of attribution estimates, the project will employ small ensembles based on multiple initialization times, allowing to separate the climate-change signal from sub-nudged internal atmospheric variability, and estimate changes in the predictability of weather extremes. The framework will be applied to a range of Mediterranean high-impact events, initially focusing on flood-producing precipitation extremes and subsequently extending to additional hazards, including windstorms, heatwaves and compound events.

The project will deliver a transferable methodology for event attribution, a unique dataset of factual and counterfactual simulations, and new insights into the physical mechanisms through which climate change influences Mediterranean weather extremes. The outcomes of MOSAIC-MED will be relevant to ongoing research activities within the Horizon Europe SUNRISE project (Grant Agreement No. 101295874) and will contribute more broadly to the development of advanced climate-risk assessment and adaptation methodologies.

1. Scientific Background and Rationale

The Mediterranean region is recognized as one of the world's major climate-change hotspots, where rising temperatures are expected to increase the frequency and intensity of high-impact weather and climate extremes (**Giorgi, 2006**; IPCC, 2021). Recent years have witnessed devastating floods, severe windstorms, prolonged heatwaves and compound events producing substantial socio-economic impacts across Europe and the Mediterranean basin (Fowler et al., 2021; Athanase et al., 2024).

Understanding the extent to which anthropogenic climate change contributes to these events is therefore a major scientific challenge and a prerequisite for improving climate adaptation and risk management strategies.

Event attribution has become a key framework for investigating the influence of climate change on individual extreme events (Shepherd, 2016). Traditional probabilistic approaches estimate changes in event likelihood or intensity using large ensembles of climate simulations, but they often provide limited insight into the physical mechanisms driving individual events, particularly in regions characterized by complex topography, strong land–sea contrasts and intense mesoscale processes (Athanase et al., 2024).

In recent years, storyline-based attribution has emerged as a complementary approach that investigates how a specific event would have evolved under different climatic conditions while maintaining a circulation pattern consistent with the observed event (Hazeleger et al., 2015; Shepherd et al., 2018; van Garderen et al., 2021). This framework enables physically interpretable "what-if" scenarios and provides a direct assessment of the thermodynamic contribution of climate change to extreme events.

For the Mediterranean region, attribution studies face an additional challenge because many high-impact events are strongly controlled by mesoscale and convective processes that cannot be adequately represented by current global climate models. Extreme precipitation, flash floods and severe convective storms arise from complex interactions among large-scale circulation, moisture transport, air–sea exchanges and topographic forcing, highlighting the need for kilometre-scale numerical simulations (Fowler et al., 2021).

MOSAIC-MED (MOLOCH Storyline Attribution of Mediterranean Extreme Events) addresses this challenge by combining recent advances in storyline attribution with convection-permitting simulations performed using the MOLOCH atmospheric model. MOLOCH has been extensively applied to the simulation of Mediterranean high-impact weather events and provides a physically consistent framework for dynamical downscaling of ERA5 reanalysis data at kilometre-scale resolution (Malguzzi et al., 2006, Davolio et al., 2009, Davolio et al., 2010, *Giovannini et al., 2021*, Stocchi et al., 2026).

A key innovation of MOSAIC-MED is the use of thermodynamic climate perturbations derived from circulation-constrained Destination Earth storylines (Hoffmann et al., 2023; Athanase et al., 2024, Grayson et al., 2026; John et al., 2026). Unlike traditional pseudo-global-warming approaches based on climatological perturbations, this framework allows the climate-change signal to depend explicitly on the atmospheric circulation regime associated with the investigated event. Furthermore, small ensembles based on multiple initialization times will be employed to quantify internal atmospheric variability and improve the robustness of attribution estimates (Buizza, 2001).

The methodology will initially focus on flood-producing precipitation extremes and will subsequently be extended to additional high-impact Mediterranean hazards. Through this approach, MOSAIC-MED will contribute to the development of physically based attribution methodologies and provide new insights into the mechanisms through which climate change influences Mediterranean weather extremes

2. Scientific Objectives

The overall goal of MOSAIC-MED is to develop and apply a convection-permitting attribution framework to investigate the influence of anthropogenic climate change on Mediterranean weather extremes through the integration of Destination Earth climate storylines, pseudo-global-warming experiments and high-resolution MOLOCH simulations.

The specific objectives are:

O1. Develop a convection-permitting storyline attribution framework. Develop and implement an attribution framework combining MOLOCH simulations with thermodynamic climate perturbations derived from circulation-constrained Destination Earth storylines, enabling physically consistent assessments of climate-change impacts on Mediterranean weather extremes.

O2. Quantify and understand climate-change impacts on Mediterranean weather extremes. Apply the framework to historical and emerging high-impact events to quantify how anthropogenic climate change modifies their intensity, duration, spatial extent and associated meteorological processes. Particular emphasis will be placed on flood-producing precipitation extremes while maintaining a broader focus on windstorms, heatwaves and compound events.

O3. Quantify uncertainty and improve attribution robustness. Implement an ensemble framework based on multiple initialization times for both factual and counterfactual simulations in order to separate the climate-change signal from internal atmospheric variability and numerical uncertainty. The ensemble framework will also provide an opportunity to investigate potential changes in event predictability under different climate conditions.

O4. Develop a transferable attribution framework for Mediterranean hazards. Demonstrate the applicability of the methodology across multiple hazard types and support future climate-risk assessments and adaptation studies.

3. Methodology

The overall MOSAIC-MED workflow is summarized in Figure 1. The framework combines high-resolution MOLOCH simulations driven by ERA5 reanalysis data with thermodynamic climate perturbations derived from Destination Earth storylines. Factual and counterfactual simulations are performed using a common modelling framework, while ensembles based on multiple initialization times are employed to quantify internal atmospheric variability and improve the robustness of attribution estimates. The proposed methodology builds upon preliminary attribution experiments recently conducted for the Emilia-Romagna May 2023 flood event (Albo, 2025), which demonstrated the feasibility of combining convection-permitting simulations, pseudo-global-warming approaches and ensemble-based uncertainty quantification within a Mediterranean event-attribution framework.

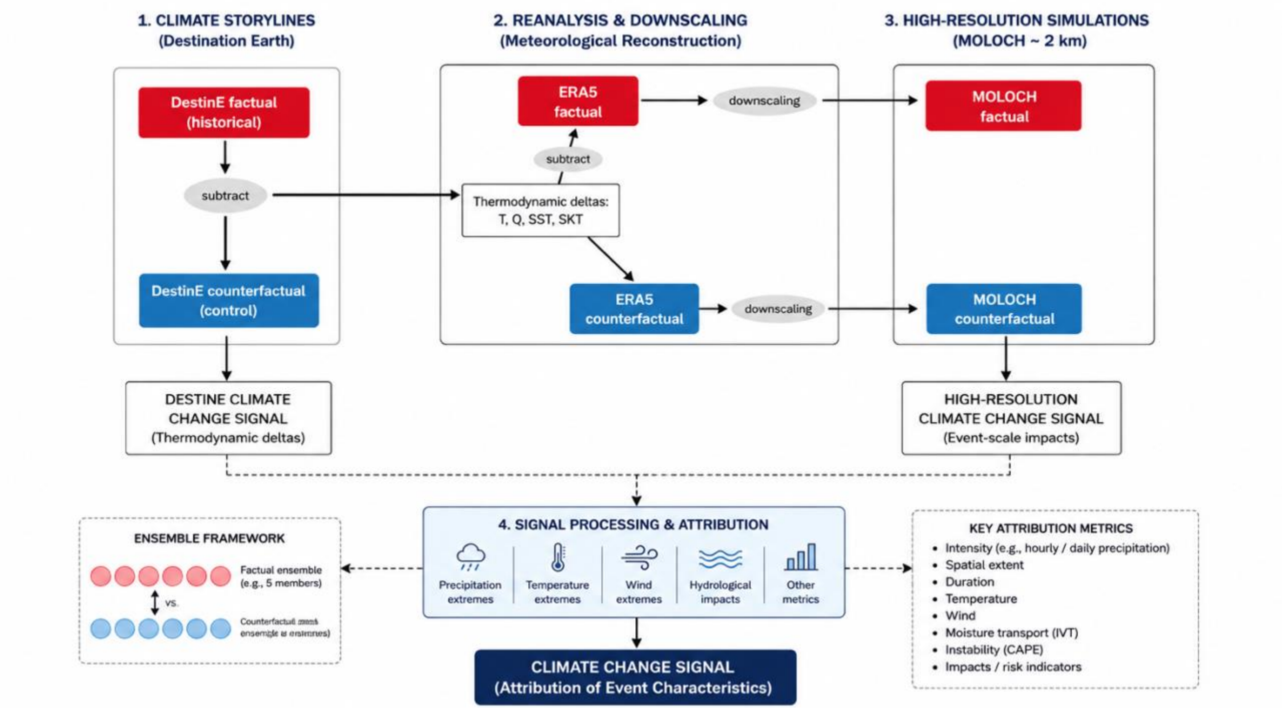

Figure 1. Workflow of the MOSAIC-MED framework. ERA5 reanalysis provides the initial and boundary conditions for the factual simulations. For the counterfactual experiments, thermodynamic climate perturbations derived from circulation-constrained Destination Earth storyline simulations are applied to the ERA5 fields to generate modified initial and boundary conditions representative of an alternative climate background. The climate perturbations are obtained from spectrally nudged global simulations and are designed to preserve consistency with the large-scale atmospheric circulation associated with the investigated event. Both factual and counterfactual simulations are dynamically downscaled using the convection-permitting MOLOCH model (~1.7–2 km resolution), with spectral nudging applied to constrain the large-scale atmospheric evolution while allowing mesoscale and convective processes to develop freely. Small ensembles based on multiple initialization times are generated for both factual and counterfactual conditions in order to quantify internal atmospheric variability and improve the robustness of attribution estimates. The comparison between factual and counterfactual ensembles provides a physically based estimate of the climate-change signal associated with Mediterranean weather extremes.

3.1 Event Selection

MOSAIC-MED will investigate a range of Mediterranean high-impact weather extremes through a physically based attribution framework. The initial focus will be on flood-producing precipitation events, while the methodology is designed to be transferable to additional hazards, including windstorms, heatwaves and compound events.

Benchmark cases will be selected according to their socio-economic relevance, representation of key Mediterranean weather processes and availability of observational datasets. Potential case studies include major recent Mediterranean events such as Storm Minerva (2023), while maintaining flexibility to investigate additional high-impact weather extremes occurring during the project period.

3.2 Factual Simulations

As illustrated in Figure 1, the factual simulations will be performed using the non-hydrostatic MOLOCH atmospheric model at convection-permitting resolution (~2 km), initialized and driven by ERA5-derived initial and boundary conditions. The simulations will employ spectral nudging to constrain the large-scale atmospheric circulation to the ERA5 reanalysis while allowing the model to explicitly develop mesoscale and convective-scale processes. This modelling framework enables a physically consistent representation of the mechanisms responsible for high-impact Mediterranean weather extremes, including intense precipitation, severe convective storms and strong wind events.

For each selected event, factual simulations will be initialized from ERA5 and integrated over a period sufficient to capture the complete event evolution, including the large-scale atmospheric conditions preceding the event and the associated mesoscale development. These simulations will provide the reference representation of the observed event against which the corresponding counterfactual simulations will be compared.

3.3 Construction of Counterfactual Storylines

The counterfactual simulations will be generated by applying thermodynamic climate perturbations derived from Destination Earth storyline simulations to the ERA5 initial and boundary conditions used in the factual experiments (Figure 1). This approach follows the pseudo-global-warming (PGW) framework (Schär et al., 1996; Liu et al., 2017), while extending it through the use of circulation-constrained climate storylines specifically designed to preserve consistency with the large-scale atmospheric conditions associated with the investigated event (van Garderen et al., 2021; Athanase et al., 2024).

The climate perturbations will be derived from spectrally nudged global simulations developed within the Destination Earth initiative (John et al. 2026). Unlike traditional PGW approaches based on climatological perturbations derived from climate model projections, these simulations provide event-specific thermodynamic changes that explicitly account for the interaction between climate change and the large-scale circulation regime. As a result, the imposed perturbations are physically coherent with the meteorological conditions characterizing the selected event.

The perturbations will be applied to the thermodynamic fields of the ERA5 reanalysis, including temperature, humidity and other relevant atmospheric variables, while preserving the large-scale dynamical evolution of the event. The resulting modified atmospheric state represents a physically plausible climatic background state to simulate the unfolding of the event under counter-factual climatic conditions.

Counterfactual simulations will be performed using the same MOLOCH configuration adopted for the factual experiments, including spectral nudging towards the perturbed large-scale atmospheric fields. This strategy ensures consistency between the storyline forcing and the regional model response, while allowing the development of event-specific mesoscale and convective processes. The comparison between factual and counterfactual ensembles will provide a quantitative estimate of the climate-change signal and enable a process-based investigation of how anthropogenic warming influences the intensity, spatial structure and physical mechanisms of Mediterranean weather extremes (Shepherd, 2016; Shepherd et al., 2018).

3.4 Ensemble Framework

As shown in Figure 1, both factual and counterfactual simulations will be performed as small ensembles based on multiple initialization times preceding the event. This time-lagged ensemble strategy is designed to quantify the uncertainty associated with sub-nudged scale internal atmospheric variability and the limited predictability of high-impact weather events, particularly those involving strong mesoscale and convective processes (Buizza, 2001; Calvo-Sancho et al., 2026).

For each case study, a set of equally plausible factual and counterfactual realizations will be generated using identical modelling configurations but different initialization times. The resulting ensemble spread will provide an estimate of the sensitivity of the simulated event to initial conditions and will help distinguish the climate-change signal from variability arising from the chaotic nature of the atmosphere.

By comparing factual and counterfactual ensembles rather than individual simulations, MOSAIC-MED will provide a more robust assessment of the influence of anthropogenic climate change on Mediterranean weather extremes and improve the physical interpretation of attribution results.

3.5 Attribution Diagnostics

Climate-change impacts will be assessed through comparisons of factual and counterfactual ensembles using hazard-specific diagnostics. Analyses will focus on changes in event intensity, duration, spatial extent and associated physical drivers, including atmospheric moisture transport, instability and thermodynamic conditions. The framework is designed to be applicable across multiple hazard types.

3.6 Cross-Event Synthesis

Results from different case studies will be compared to identify common patterns and physical drivers of climate-change impacts across Mediterranean weather extremes. This synthesis will support the development of a transferable attribution framework applicable to multiple hazard types and future climate-risk assessments.

4. Computing Resources Requested

The requested resources are based on benchmark tests performed on the ECMWF ATOS system using the Emilia-Romagna May 2023 flood event. Simulations were conducted with the MOLOCH convection-permitting model at approximately 1.7–2 km horizontal resolution over a domain of about 770 × 960 grid points. The benchmark configuration was executed on 3 compute nodes (384 CPU cores) and provides the basis for the resource estimates summarized in Table 1.

Parameter	**Value**
Horizontal resolution	~1.7–2 km
Domain size	~770 × 960 grid points
Simulation length	96 h (typical)
Computational cost per simulation	9,552 SBU
Output per simulation	~175 GB
Simulations per event	10 (5 factual + 5 counterfactual)
Computational cost per event	~95,500 SBU
Output per event	~1.75 TB
Maximum number of events per year	6
Core production cost per year	~0.57 million SBU
Core output per year	~10.5 TB

Table 1. Summary of the computational requirements of the MOSAIC-MED framework. Resource estimates are based on benchmark tests performed on the ECMWF ATOS system using a 96-hour convection-permitting MOLOCH simulation of the Emilia-Romagna May 2023 flood event. The benchmark configuration employed a horizontal resolution of approximately 1.7–2 km over a domain of about 770 × 960 grid points and was executed on 3 compute nodes (384 CPU cores). Event-level estimates assume an ensemble of five factual and five counterfactual simulations. Annual requirements are based on up to six analysed events per year and represent the core production cost before accounting for additional resources required for preprocessing, post-processing, sensitivity experiments and methodological developments

Additional resources are required for preprocessing, post-processing, diagnostic analyses, sensitivity experiments, reruns and the investigation of additional high-impact weather events occurring during the project period. Furthermore, some case studies may require longer integration periods than the benchmark configuration and additional ensemble experiments to assess uncertainty and attribution robustness. To account for these activities and for possible variations in simulation length, domain size and number of analysed events, MOSAIC-MED requests approximately **3 million SBU per year**, corresponding to **9 million SBU** over the 2027–2029 period.

The requested archive storage is **15 TB per year**, corresponding to approximately **45 TB** over the full project duration

4.1 Technical Characteristics of the Code

The project will employ the non-hydrostatic MOLOCH atmospheric model, a convection-permitting limited-area model developed at CNR-ISAC and widely used for Mediterranean weather applications. MOLOCH is written in Fortran and parallelized using MPI domain decomposition, enabling efficient execution on modern HPC systems.

Simulations will be performed at approximately 1.7–2 km horizontal resolution over domains of about 770 × 960 grid points, using spectral nudging to constrain the large-scale circulation while explicitly resolving mesoscale and convective processes.

The proposed framework builds upon experience gained through the ECMWF Special Project SPITSTOC-2023, in which MOLOCH and its associated workflows were successfully ported, optimized and extensively used on ECMWF HPC facilities. Resource estimates presented in this proposal are therefore based on direct operational experience and benchmark tests performed on the ATOS system.

5. Expected Outcomes and Impact

MOSAIC-MED will deliver a convection-permitting framework for the attribution of Mediterranean weather extremes, combining Destination Earth climate storylines, high-resolution MOLOCH simulations and ensemble-based uncertainty quantification. The project will produce a unique set of factual and counterfactual simulations, enabling physically based assessments of how climate change influences the intensity, duration and spatial characteristics of high-impact Mediterranean events.

Scientific outcomes will include methodological advances in event attribution, peer-reviewed publications and unique datasets of factual and counterfactual simulations for Mediterranean high-impact weather events. More broadly, MOSAIC-MED will contribute to the development of transferable methodologies for climate-risk assessment, climate services and adaptation studies across the Mediterranean region.

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