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:	Exploiting Coupled, High-resolution modelling to simulate severe mediterranean cyclOgenesES (ECHOES)
Computer Project Account:	SPITRICC
Principal Investigator(s):	Antonio Ricchi
Affiliation:	University of L'Aquila CETEMPS (Center of Excellence in Telesensing of Environment and Model Prediction of Severe Events), Department of Physical and Chemical Sciences (DSFC), Italy
Name of ECMWF scientist(s) collaborating to the project (if applicable):	
Start date of the project:	01/01/2025
Expected end date:	31/12/2027

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	(SBU)	60,000,000	15,457,373	53,000,000	26,803,240
Data storage capacity	(Gbytes)	26,000	50,000	20,000	≈ 20,000

The 2026 HPCF allocation of 53,000,000 SBU consists of the 38,000,000 SBU baseline (reduced from the 50,000,000 SBU originally approved in the three-year plan) plus a 15,000,000 SBU supplementary allocation approved in June 2026; HPCF usage is reported as of 29 June 2026 (50.6% of the year). Storage is actively managed model output is continuously offloaded to the UNIVAQ/CETEMPS archive and purged from the ATOS work file system, so the instantaneous footprint is kept within the 20 TB allocation while a larger cumulative volume is cycled through it (the source of the 2025 over-quota, since resolved). The 20 TB allocation is sufficient and no additional storage is requested.

Summary of project objectives

ECHOES aims to improve the understanding and the high-resolution simulation of extreme Mediterranean cyclones Tropical-Like Cyclones (TLCs, “Medicanes”) and Explosive Cyclogeneses (EC) through convection-permitting, coupled atmosphere-ocean-wave modelling. The project pursues four objectives: (i) to reforecast a selection of ten severe cyclones of the last three decades with uncoupled and fully coupled short-term simulations, quantifying the added value and cost of coupling and optimising the air-sea flux parameterisations; (ii) to produce a 30-year (1994-2023) convection-permitting atmospheric reforecast with WRF using the optimised configuration; (iii) to produce two 30-year ocean-wave hindcasts with the structured ROMS-WW3 and the unstructured SHYFEM-WW3 suites, forced by the atmospheric reforecast; and (iv) to assemble high-resolution (up to 500 m along coastlines) open-access datasets of atmospheric and ocean-wave variables for climatological and machine-learning applications, with particular attention to high-impact variables (hail and hail size, lightning, storm surge, significant and maximum wave height). ECHOES is the partial continuation of the ASIM-CPL special project on air-sea-wave interactions and targets both scientific advances and societal applications such as early warning and coastal-risk assessment.

Summary of problems encountered

No problem has hindered the implementation or the continuation of the project. The main issue concerns the pace of resource consumption rather than any technical failure. The first year (2025) was dominated by configuration, optimisation and benchmarking activities grid stabilisation, physics tuning, the 5 km reanalysis spin-up and the porting of the COAWST and SHYFEM-WW3 suites a large fraction of which was carried out on local CETEMPS/INFN servers and on a deliberately conservative ramp-up of the ATOS production runs. As a consequence, only 15.46 M SBU (about 26%) of the 2025 allocation was billed, and the data-storage accounting temporarily exceeded the nominal quota because of an unoptimised retention policy. Both aspects have been addressed in 2026: production has been scaled up substantially (50.6% of the larger 2026 allocation already consumed by the end of June), an automatic offload-and-purge policy now keeps the storage footprint within 20 TB, and a scientifically urgent ensemble/attribution campaign on two landmark 2026 storms (Section 6.6) has been added to fully exploit the available envelope. Minor technical issues occasional restarts of coupled ensemble members and post-processing reruns were resolved without significant delay.

Summary of plans for the continuation of the project

In the second half of 2026 the project will: (a) complete the multi-physics/multi-model ensemble, ocean-sensitivity and Pseudo-Global-Warming (PGW) attribution campaign on Storm Harry (January 2026) and Medicane Jolina (March 2026), including the standalone WW3/SWAN wave blocks; (b) continue the migration of the long-term atmospheric reanalysis from 5 km to the 3 km convection-permitting configuration, validated over representative winter and summer quarters; and (c) advance the coupled SHYFEM-WW3 and COAWST (WRF-ROMS-WW3) hindcasts for the selected events. In 2027 the allocation will be concentrated on the core scientific exploitation of the produced reanalyses: a systematic, fully coupled, very-high-resolution study of the principal Mediterranean high-impact events at least ten medicanes together with rapid-cyclogenesis, wind-wave-storm and heatwave cases with SST-impact/ocean-role experiments and km-scale ensemble reduction, complemented by a targeted coupled reanalysis of the most extreme-event-rich years. These activities motivate the request, for 2027, of the full HPCF allocation foreseen in the original project plan (detailed in the resource-justification section below).

List of publications/reports from the project with complete references

Peer-reviewed and submitted articles

- Serafini, P., Ricchi, A., Marsigli, C., D'Amico, C., Nastasi, M., Pelosini, R., Ferretti, R. (2026). *Multi-model high-resolution analysis of Tropical-Like Cyclone Daniel with WRF and ICON: peculiarities and sensitivity to convection schemes.* Submitted to *Weather and Climate Dynamics* (Copernicus); preprint egusphere-2026-1697. Status: two peer reviews received, author response in preparation.
- Favaretto, C., Barbariol, F., Benetazzo, A., Cavaleri, L., Falcieri, F. M., Ferrarin, C., Ferretti, R., Menegon, S., Nastasi, M., Redaelli, G., Ricchi, A., Ruol, P. (2026). *An Ensemble-Based Coastal Flooding Index for Early Warning Applications.* Submitted to *Weather and Climate Dynamics* (Copernicus); preprint egusphere-2026-2285.
- Ricchi, A., Ayim, O. V., Alberoni, P. P., Ferretti, R. (2026). *Analysis of an Intense Hail Event in the Pó Valley using Observation and the WRF Model.* Accepted/in production (*Atmospheric Research*); preprint SSRN 6270278.

Manuscripts in preparation

- Serafini, P., Ricchi, A., D'Amico, C., Nastasi, M., Ferretti, R. *Advancing cyclones tracking with HIMPACT: HIgh-resolution Multilevel Python-based Algorithm for cyclones' Centroid Tracking.* Target: *Atmosphere* (MDPI). Status: draft completed, internal review ongoing.
- D'Amico, C., Nastasi, M., Carrió, D., Serafini, P., Ricchi, A., Ferretti, R. *Improving forecast skills for Mediterranean Tropical-like Cyclones using Data Assimilation: the case study of Medicane Qendresa.* In preparation.
- *Ensemble reduction for probabilistic downscaling of severe weather events in the Mediterranean region.* Manuscript in preparation (CETEMPS ensemble group).
- Serafini, P., Ricchi, A., Blahak, U., Ferretti, R. *Advancing hail prediction in complex orography: a comparative study of WRF-HAILCAST and ICON-EMVORADO over central Italy.* In preparation; simulations in progress.

Conference contributions

- Serafini et al. Multi-model high-resolution analysis of Mediterranean Hurricane Daniel with WRF and ICON. EGU General Assembly 2025, Vienna (EGU25-19128).
- Ricchi, Ferretti, Pantillon, Serafini, Dafis, Menna, Martellucci, Carrió On the role of air-sea-wave interaction in developing destructive TLC Daniel. MetMed 2025, Toulouse.
- Carrió, Serafini, Pantillon, Dafis, Menna, Martellucci, Ferretti On the role of air-sea-wave interaction in developing destructive TLC Daniel. EMS Annual Meeting 2025, Ljubljana (EMS2025-421).
- Ferretti, Miglietta, Sancho, Ricchi On the role of ocean structure in the Valencia flood development. EMS Annual Meeting 2025, Ljubljana (EMS2025-352).
- Favaretto, Barbariol, Ferretti, Ferrarin, Benetazzo, Ricchi, Ruol An ensemble-based early-warning index for coastal flooding alerts. 4th International Workshop on Waves, Storm Surges and Coastal Hazards, 2025.
- Nastasi et al. Probabilistic wave and storm surge forecasting at regional scale using reduced ensemble forcings. 4th International Workshop on Waves, Storm Surges and Coastal Hazards, Santander, 2025.
- Ricchi et al. Sea response to a sudden strong wind and its predictability (the Neverin event). 4th International Workshop on Waves, Storm Surges and Coastal Hazards, Santander, 2025.
- Serafini et al. Multi-model high-resolution analysis of TLC Daniel with WRF and ICON. CNR-ISAC Summer School 2025.
- Serafini et al. Peculiarità dei modelli WRF ed ICON in simulazioni ad alta risoluzione del ciclone mediterraneo simil-tropicale Daniel. AISAM Students' Conference 2025.

- D'Amico, Nastasi, Carrió, Serafini, Ricchi, Ferretti Improving forecast skills for Mediterranean TLCs using Data Assimilation: Medicane Qendresa (poster). AISAM 6th National Congress of Meteorology (CN6), Brescia, February 2026.
- Serafini et al. Multi-model high-resolution analysis of Mediterranean TLC Daniel with WRF and ICON: peculiarities and sensitivity to convection schemes. AISAM 6th National Congress of Meteorology (CN6), Brescia, 2026.
- Serafini, Ricchi, Blahak, Ferretti Advancing hail prediction in complex orography: WRF-HAILCAST and ICON-EMVORADO over central Italy. ICCARUS 2026.
- Serafini et al. Multi-model high-resolution analysis of TLC Daniel with WRF and ICON. EMS Annual Meeting 2026 (scheduled).

Summary of results

The work carried out under ECHOES in 2025-2026 is organised here in six interlocking work packages: the long-term convection-permitting reanalysis and its observational validation (6.1); a multi-model, multi-physics study of TLC Daniel (6.2); data assimilation for medicane prediction (6.3); the HIMPACT objective cyclone tracker (6.4); ensemble strategies and ensemble reduction (6.5); and the coupled atmosphere-ocean-wave activities, including the 2026 air-sea/aerosol attribution campaign on Storm Harry, Medicane Jolina and the Pó Valley hail case (6.6). Together they cover the full ECHOES chain from the optimisation of the modelling set-up to the production and exploitation of high-resolution datasets and they are the activities on which the 2026 allocation has been spent. Part of the multi-decadal validation and of the ensemble-reduction work reported in Sections 6.1 and 6.5 was carried out within the closely connected national project PROMETEO (PNRR), which shares the same WRF + SHYFEM-WW3 modelling framework and several team members with ECHOES; where PROMETEO material is used it is explicitly attributed, and it was produced on national HPC infrastructure (it did not consume ECHOES SBU on the ATOS HPCF).

6.1 Long-term coupled reanalysis and observational validation

The backbone of ECHOES is a multi-decadal, hourly Mediterranean reanalysis in which a convection-permitting WRF atmospheric reanalysis drives an offline coupled ocean-wave model (Figure 1). A first 30-year (1994-2023) atmospheric reanalysis has been completed with WRF (basin-scale Mediterranean grid, sixty hybrid vertical levels with the lowest level at 30 m, double-moment microphysics, Kain-Fritsch convection, a non-local PBL scheme and hourly ERA5 SST updates); a bespoke reduction of the surface drag coefficient over waters shallower than 50 m (GEBCO bathymetry) improves the representation of nearshore winds. The reanalysis is produced in reforecast mode (Figure 2): 54-hour runs initialised daily at 00 UTC with ECMWF-IFS initial and boundary conditions, the first 6 hours discarded as spin-up and replaced by the last 6 hours of the previous run, which optimises both performance and continuity. The mean sea-level pressure and 10 m wind fields produced by WRF are then used to force the coupled SHYFEM-WW3 ocean-wave system, so that the reanalysis delivers a self-consistent multi-decadal description of wind, sea level and waves over the whole basin. The configuration is being migrated to the target 3 km convection-permitting set-up on the ATOS HPCF, tested over a representative winter and a representative summer quarter ahead of the full ECHOES production.

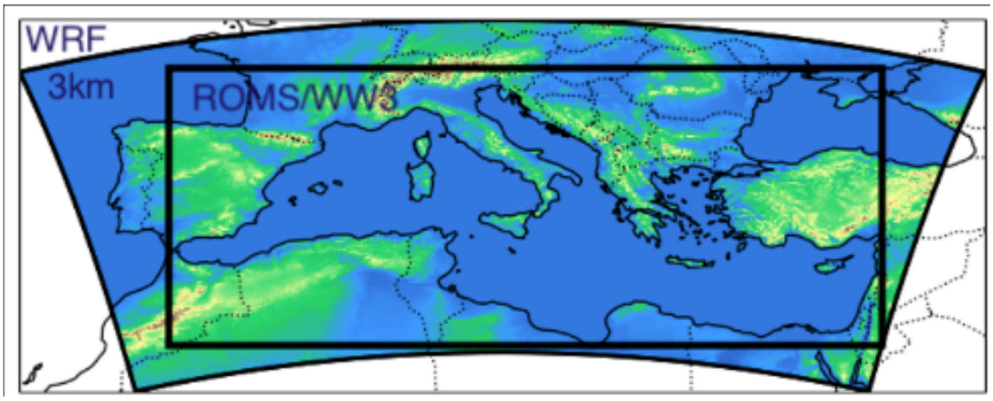

Figure 1. *WRF Mediterranean computational domain used for the ECHOES atmospheric reanalysis and reforecast (blue), with the structured ROMS/WW3 ocean-wave grid (black box). Adapted from the ECHOES project plan.*

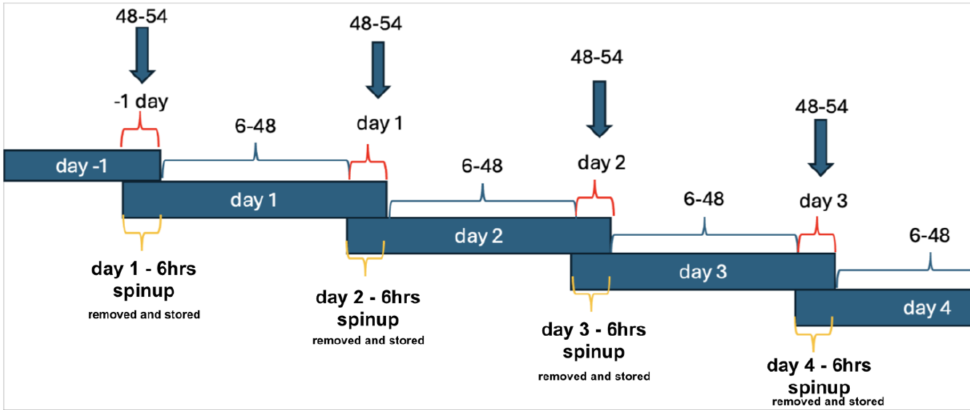

Figure 2. *Reforecast strategy for the long-term WRF simulations: overlapping 54-hour runs initialised daily at 00 UTC, with the first 6 hours (spin-up) of each run replaced by the last 6 hours of the previous one. Adapted from the ECHOES project plan.*

The ocean-wave component is solved on the unstructured SHYFEM-WW3 grid (Figure 3), which spans the entire Mediterranean with roughly 163,000 triangular elements and a resolution ranging from about 12 km in the open sea to approximately 500 m along the coast, with an open boundary at the Gibraltar Strait. The same finite-element grid is shared by the hydrodynamic (SHYFEM) and the spectral wave (WW3) models, so that the coupling explicitly accounts for the contribution of waves to total sea level (set-up and set-down), the modulation of wave propagation by tides and surge (refraction, shoaling, breaking) and the effect of currents and sea-level changes on wave generation and dissipation. This is the same unstructured suite that will be run, forced by the convection-permitting reforecast, to deliver one of the two ECHOES 30-year ocean-wave hindcasts.

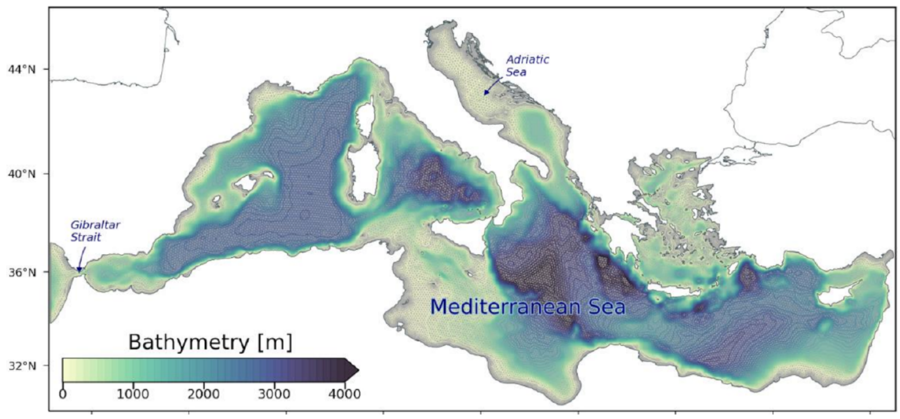

Figure 3. *Unstructured SHYFEM-WW3 computational grid covering the Mediterranean Sea (≈ 163,000 triangular elements; ≈ 12 km offshore to ≈ 500 m along the coast), shared by the hydrodynamic and spectral-wave models and forced by the WRF reanalysis. From the shared ECHOES/PROMETEO modelling framework (PROMETEO project).*

The multi-decadal dataset has been validated against independent observations within the shared framework (PROMETEO project). The WRF 10 m wind speed compares very well with satellite-altimeter winds (Envisat, Jason-1, Jason-2) over 2010-2019, with essentially zero mean error, a mean absolute error of ≈ 1.6 m s^{-1} and a regression slope of ≈ 0.95-0.96 (Figure 4). The sea level was assessed against 29 Mediterranean tide-gauge stations and the significant wave height against 34 wave-buoy stations: across the tide-gauge network the model attains correlation coefficients mostly in the 0.75-0.92 range with RMSE of 0.05-0.17 m, and across the wave-buoy network correlation coefficients of ≈ 0.63-0.93 with centred RMSE of ≈ 0.18-0.45 m. The corresponding multi-decadal climatology (1993-2024) is illustrated in Figure 5 by the monthly 99th-percentile significant wave height for the four seasons, which captures the well-known winter maxima in the Gulf of Lion, the Sicily Channel and the Aegean. This extensive validation of the shared chain de-risks the ECHOES production phase: the modelling system that ECHOES is running on ATOS is the one validated here at multi-decadal scale.

Validation of the reanalysis (PROMETEO framework)	Reference/network	Stations	Skill (range)
10 m wind speed U10	Satellite altimeters (Envisat, Jason-1/2), 2010-2019	3 missions	ME ≈ 0; MAE ≈ 1.6 m s^{-1}; slope ≈ 0.95
Sea level (water level)	Tide-gauge stations, Mediterranean	29	CC ≈ 0.69-0.92; RMSE 0.05-0.17 m
Significant wave height Hs	Wave-buoy stations, Mediterranean	34	CC ≈ 0.63-0.93; CRMSE 0.18-0.45 m

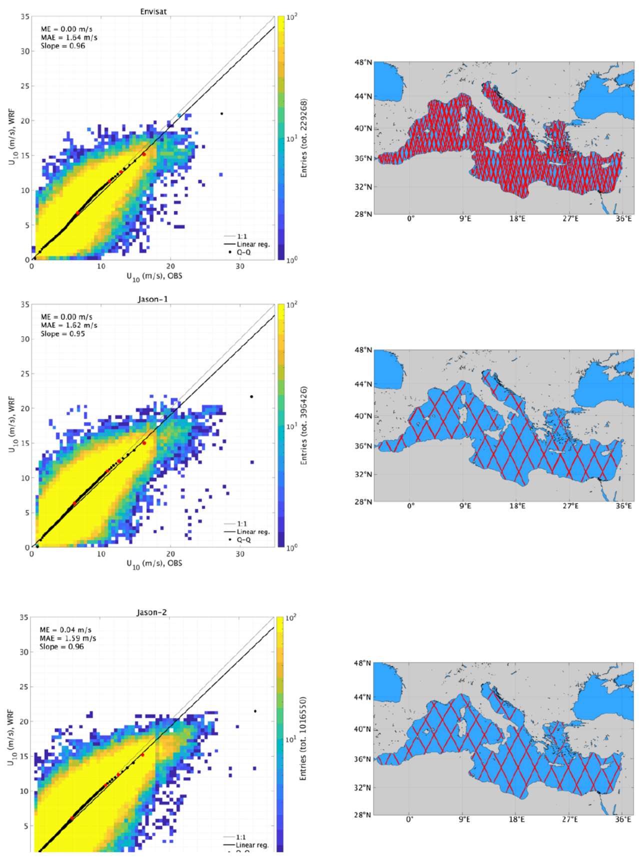

Figure 4. *Validation of WRF 10 m wind speed against satellite-altimeter winds (Envisat, Jason-1, Jason-2) over the Mediterranean (2010-2019): density scatter of model versus observed U10 with mean error, mean absolute error and regression slope (left), and altimeter ground-track sampling (right). From the shared ECHOES/PROMETEO framework (PROMETEO project).*

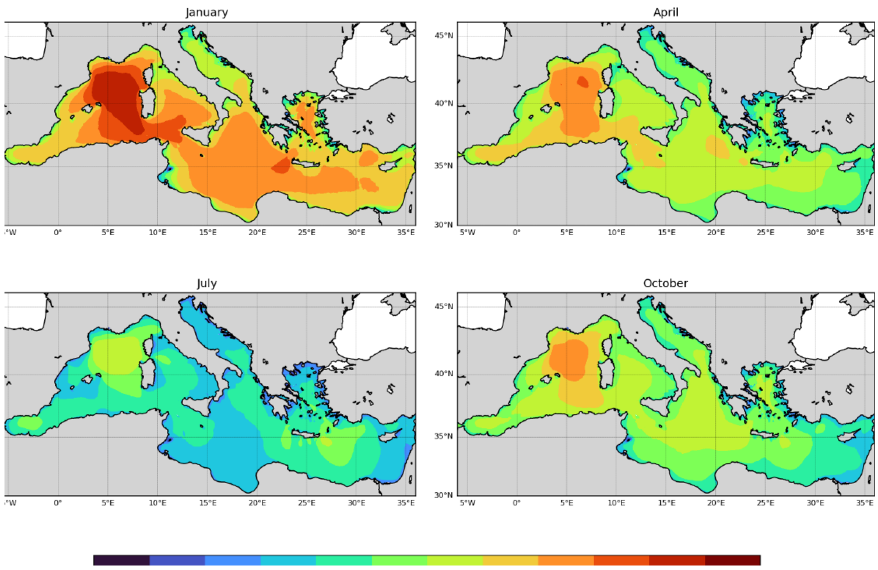

Figure 5. *Multi-decadal climatology from the coupled reanalysis: monthly 99th-percentile significant wave height (Hs) averaged over 32 years (1993-2024) for four months representative of the seasons (January, April, July, October). From the shared ECHOES/PROMETEO framework (PROMETEO project).*

6.2 Multi-model, multi-physics analysis of Tropical-Like Cyclone Daniel

Medicane Daniel (4-12 September 2023) is one of the most destructive Mediterranean cyclones on record, responsible for catastrophic flooding in Greece during its baroclinic phase and in Libya (Derna) at tropical-like maturity. Its long, multi-stage life cycle genesis, extratropical development, tropical transition, mature TLC and dissipation makes it a uniquely stringent benchmark for model physics, because a single framework must represent large-scale forcing and mesoscale convective organisation with comparable skill. Under ECHOES, Daniel has been simulated at ≈ 2 km with two state-of-the-art models, WRF v4.6.0 and ICON v2.6.6, in Limited-Area mode and configured to be as comparable as possible (single common domain, identical ≈ 2 km resolution, IFS analyses as initial and boundary conditions; Figure 6). Seven simulations sample the treatment of convection: fully explicit (EXP), parameterised deep cumulus (CU), independent shallow convection (SH) and, for ICON, the “grayzone” option (GZ).

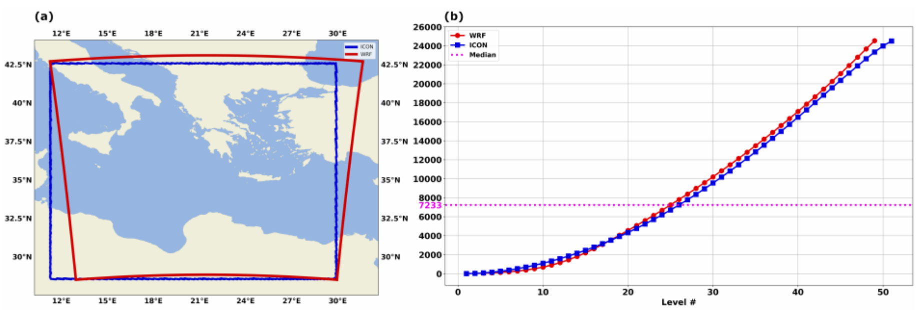

Figure 6. *Harmonised WRF-ICON experimental set-up for Daniel: (a) common 2 km domain (WRF outline in red, ICON in blue); (b) vertical-level distribution of the two models (median height as the dashed line). From Serafini et al. (2026, egusphere-2026-1697).*

The objective tracking and intensity verification (Figure 7) reveal a clear ordering of the configurations. The fully explicit WRF run (WRF-EXP) reproduces the observed track best (mean displacement RMSE ≈ 76 km, σ ≈ 48 km), followed by WRF-CU and ICON-SH, while ICON-CU and ICON-GZ are the least skilful (RMSE ≈ 113 and 111 km). Across the suite, WRF systematically produces deeper central sea-level pressures and stronger 10 m winds than ICON. The Cyclone Phase Space diagnostics (Figure 8) and the temporally averaged annular cross-sections (Figure 9) explain why: the WRF configurations build a vertically coherent warm core extending up to ≈ 300 hPa, with an eyewall-like equivalent-potential-temperature maximum that favours barotropic intensification, whereas ICON-EXP develops only a shallow warm anomaly confined below ≈ 550 hPa. The ICON-GZ (grayzone) experiment represents a critical failure mode, over-damping convective development and preventing the tropical transition, while the deep-cumulus (CU) schemes trigger an unrealistic latent-heat/pressure-deepening feedback and over-intensify the vortex.

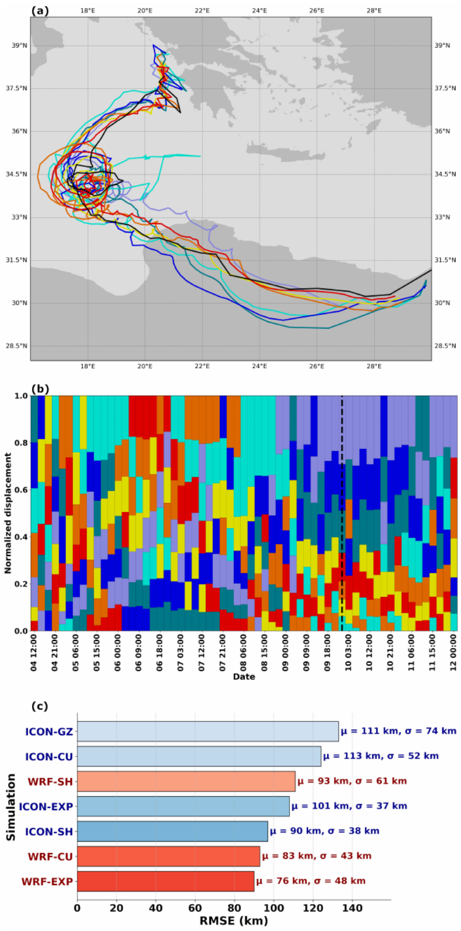

Figure 7. *Daniel verification: (a) simulated tracks of the seven WRF/ICON configurations against the observed track (black); (b) normalised hourly displacement error, stacked per time step (lower is better); (c) track displacement RMSE mean and standard deviation for each simulation. From Serafini et al. (2026, egusphere-2026-1697).*

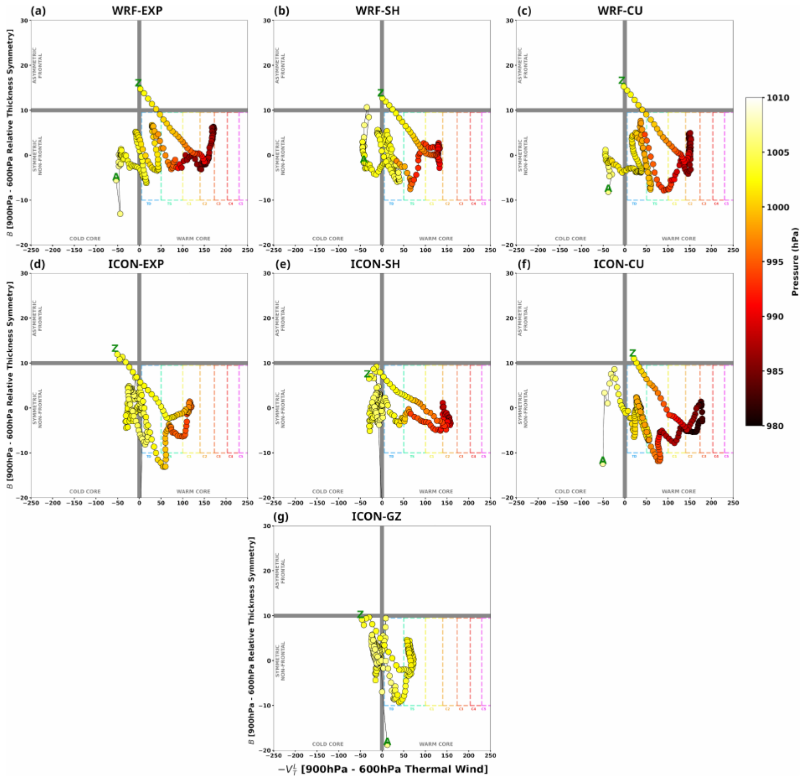

Figure 8. *Cyclone Phase Space (lower-tropospheric thermal symmetry parameter B versus lower-tropospheric thermal wind V_t^L) for each of the seven simulations (a-g); markers A-Z trace the life cycle and are shaded by central pressure. WRF configurations cross more decisively into the symmetric warm-core (tropical) quadrant. From Serafini et al. (2026, egusphere-2026-1697).*

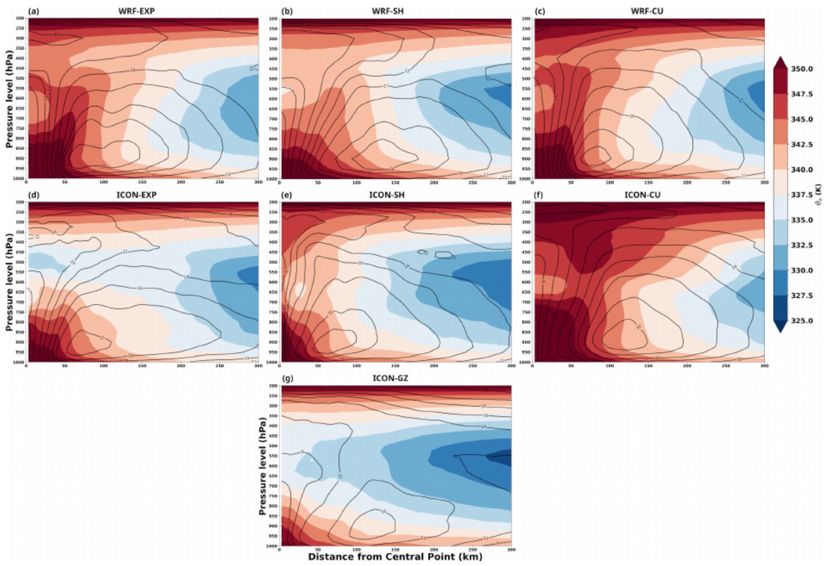

Figure 9. *Temporal Annular Symmetric Mean cross-sections of wind speed (black contours) and equivalent potential temperature (shaded) averaged over the eight time steps before landfall (mature phase), for the seven configurations. The WRF runs (top row) show a deeper, vertically coherent warm core relative to ICON. From Serafini et al. (2026, egusphere-2026-1697).*

The precipitation verification against satellite precipitation estimates via the Fraction Skill Score confirms the picture: WRF tends to over-produce and ICON to under-produce rainfall, but the WRF-SH configuration uniquely attains grid-scale skill for extreme thresholds, and the EXP and SH options retain the largest FSS for both models. Two operationally relevant conclusions follow, and they directly shape the ECHOES roadmap. First, at ≈ 2 km a "convection-permitting" simulation should not be run as purely explicit: a shallow-convection scheme acts as a bridge that lets the model resolve organised deep convection while parameterising the smaller-scale mixing that preconditions it.

Second, the dynamical equivalence of a physical option cannot be assumed across models the same nominal scheme behaves differently in WRF and ICON because of differences in discretisation, diffusion and vertical coordinate so each model requires dedicated calibration, and forecast strategies for long-lived systems must be case-specific. These findings are the scientific rationale for moving, in 2027, towards multi-physics ensembles and coupled atmosphere-ocean simulations of the full event suite.

6.3 Data assimilation for medicane prediction: Qendresa

Medicane Qendresa (6-8 November 2014) developed over the Sicily Channel, deepened rapidly and described a characteristic loop near Linosa and Malta. Under ECHOES it is used to quantify how data assimilation and domain configuration improve the short-range prediction of a medicane track. WRF three-dimensional variational assimilation (WRFDA 3D-Var, CV5 control variables) has been applied to the 36-hour window from 00 UTC 7 November to 12 UTC 8 November 2014, assimilating conventional MADIS observations, Atmospheric Motion Vectors and surface wind. The background-error covariance matrix has been built with three strategies the NMC method, an ensemble (ENS) method and a hybrid (HYB) method and the most performing one has been retained for a set of assimilation experiments run on a single-domain (1DOM) and a two-way-nested (2DOM, with a 3 km parent) configuration.

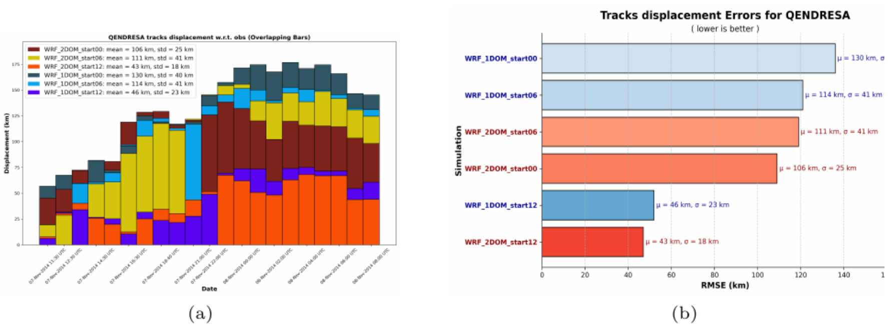

Figure 10. *Qendresa track verification: (a) hourly displacement error bars per simulation and (b) displacement RMSE (mean and standard deviation) for the IFS-driven assimilation experiments. Introducing a 3 km parent domain and assimilating conventional, AMV and surface-wind observations reduces the track error (best configuration ≈ 42 km mean displacement). Preliminary result; D'Amico et al. (in preparation).*

The preliminary results (Figure 10) show that adding the 3 km parent domain reduces both the translational error and a spurious slowdown of the cyclone, and that the assimilation of the additional observation types improves the reproduction of the cyclone core position at almost every time step, with the best configuration reaching a mean displacement of about 42 km. The analysis of the optimal background-error strategy and of the associated intensity improvement is ongoing and will be reported in the dedicated manuscript.

6.4 Objective cyclone tracking at convection-permitting scale: HIMPACT

The transition to convection-permitting resolution introduced a methodological obstacle that affects every result above: the “convective noise” of explicitly resolved deep convection produces localised pressure and vorticity anomalies that can exceed the synoptic-scale cyclone centre in magnitude, causing classical trackers to diverge especially during the baroclinic-to-tropical transition typical of medicanes. To track the ECHOES simulations robustly, the group has developed HIMPACT (HIgh-resolution Multilevel Python-based Algorithm for cyclones' Centroid Tracking; Figure 11), a tracker designed specifically for high-resolution NWP output. HIMPACT combines a multi-level geopotential analysis of the 800-950 hPa layer with a percentile-based threshold that isolates the vortex core from convective perturbations, and a convex-hull centroid logic that stabilises the trajectory where the centre is ill-defined.

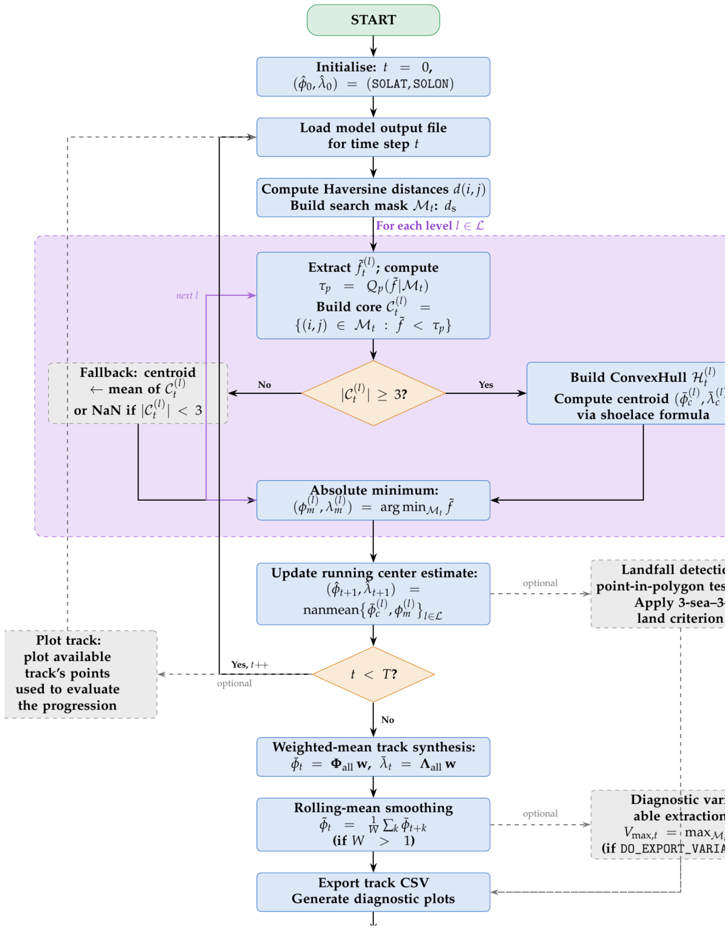

Figure 11. *Execution flow of the HIMPACT tracker: per-time-step loading of model output, Haversine search mask, per-level percentile thresholding and convex-hull centroid computation, running-centre update, weighted-mean track synthesis and rolling-mean smoothing, with optional landfall detection and Lagrangian diagnostic extraction. From Serafini et al. (in preparation).*

HIMPACT has been validated through a 63-member sensitivity ensemble exploring the number of vertical levels, the percentile threshold and the search radius. The optimal configuration five levels, fifth percentile, convex-hull centroid and a 150 km search radius reduces the track displacement RMSE by about 35% relative to single-level point-minimum tracking on a 2 km grid, while maintaining track continuity through the transition phase. Beyond positional accuracy, the modular Python framework extracts model diagnostics along the track, enabling a genuinely Lagrangian analysis of the cyclones simulated within ECHOES. HIMPACT is the tracker used to produce the Daniel and Jolina trajectories shown in this report.

6.5 Ensemble strategies and ensemble reduction

A central methodological objective of ECHOES is to make high-resolution probabilistic forecasting of high-impact Mediterranean weather computationally affordable. A regional ensemble is built by dynamically downscaling the 51-member ECMWF-IFS ensemble with WRF, and an operational downscaling suite is maintained at CETEMPS. Running the full ensemble at convection-permitting resolution is, however, prohibitively expensive, which motivates an ensemble-reduction strategy: the aim is to work with a much smaller number of members while preserving the probabilistic information of the full ensemble (ENS), i.e. keeping the probability distribution of the reduced ensemble (RENS) as close as possible to that of ENS the "relevance" of the RENS in the sense of Molteni et al. (2001). A relevant RENS frees the computational budget that can then be reinvested in resolution or in added Earth-System complexity (coupling, more sophisticated physics).

The reduction follows a two-step procedure (clustering of the ensemble fields, then selection of representative members) with two additions that were found to improve relevance. First, a dimensionality reduction is applied before clustering: the input fields are projected onto the leading

Principal Components explaining 80% of the total variance, which lets the clustering operate on the few samples (the members) against a much larger number of features (grid points × time steps). Second, hierarchical agglomerative clustering with Ward's minimum-variance criterion is preferred to complete linkage. The multivariate input comprises the IFS-ENS 10 m wind components, mean sea-level pressure and the squared 10 m wind speed (a proxy for wind stress), restricted to the Adriatic Sea for the storm-surge target area and sampled along the 0-48 h trajectory at 6-hourly steps. Fixing the number of clusters to 15 yields a 15-member RENS that requires only ≈ 30% of the simulations hence ≈ 30% of the computational cost of the 50-member ENS, while still approximating its probability distribution.

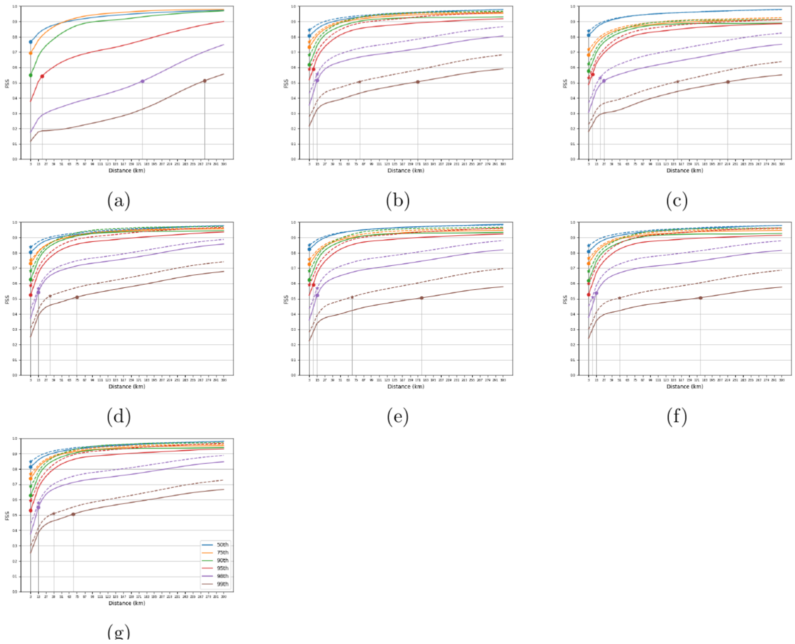

Figure 12. *Atmospheric-ensemble verification of the reduction strategy: Fraction Skill Score of 24-hour accumulated precipitation (Vaia, 29-30 October 2018) versus neighbourhood length scale, for several rainfall thresholds, comparing (a) the control member, (b) the full 51-member ensemble and (c-g) reduced ensembles of 5, 10, 15, 20 and 25 selected members; solid lines are the deterministic FSS of the ensemble mean, dashed lines the probabilistic FSS. From the CETEMPS ensemble work (Nastasi et al., in preparation; PROMETEO project).*

The atmospheric-ensemble verification confirms that the reduction preserves skill: the Fraction Skill Score of accumulated precipitation obtained from the reduced ensembles converges towards that of the full 51-member ensemble already for a few tens of selected members (Figure 12), and the Continuous Ranked Probability Score of accumulated precipitation tracks the full-ensemble behaviour through the event (Figure 13). The clustering-based selection provides marginal but consistent gains over random sampling, which nonetheless remains a competitive baseline, so the RENS is best understood as a scenario ensemble that samples physically distinct, plausible evolutions rather than their exact relative frequency.

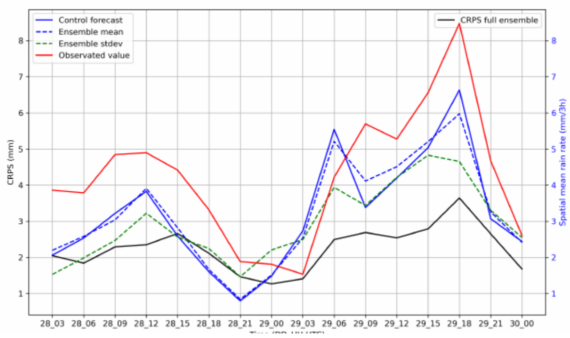

Figure 13. *Continuous Ranked Probability Score (CRPS) of 24-hour accumulated precipitation through the Vaia event for the control forecast, the ensemble mean and the full-ensemble CRPS, with the observed value for reference. From the CETEMPS ensemble work (Nastasi et al., in preparation; PROMETEO project).*

In space, the reduced ensemble reproduces both the mean and the spread of the full ensemble. For the Vaia storm over the Adriatic Sea the ENS and RENS 10 m wind fields are nearly indistinguishable in ensemble mean (≈ 15.5 versus ≈ 15.3 m s^{-1} at the storm peak) and in ensemble spread (Figure 14). At the offshore site in front of Jesolo the entry point of the nearshore modelling chain the RENS reproduces the time series of water level and significant wave height of the full ensemble with a normalised mean absolute error of the ensemble mean of only ≈ 2.1% and ≈ 1.8% respectively (Figure 15). The same statistical information is also exploited to build flow-dependent background-error covariances for ensemble-based variational assimilation (En3DVar), linking this work package to the Qendresa data-assimilation experiments of Section 6.3. Together these results underpin the probabilistic dimension of the 2026 attribution campaign described next.

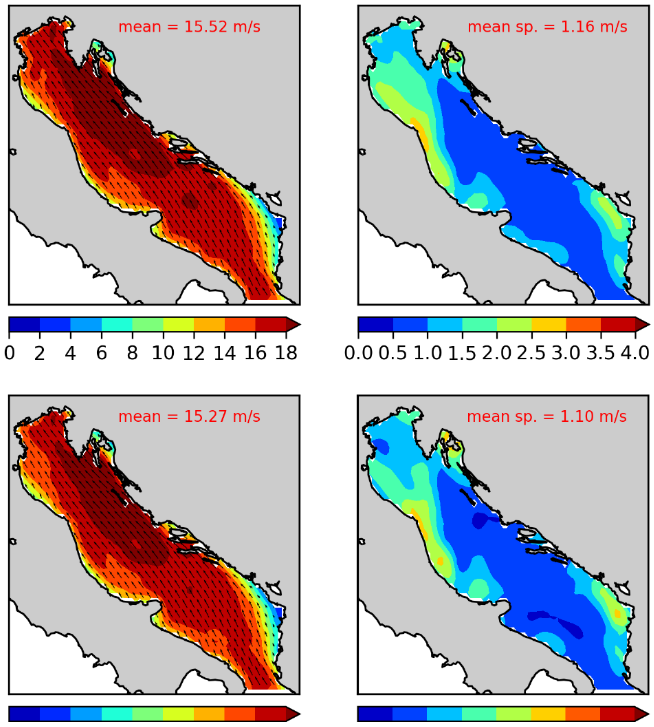

Figure 14. *Vaia storm over the Adriatic Sea: ensemble mean (left) and ensemble spread (right) of 10 m wind speed at the storm peak (18 UTC, 29 October 2018) from the full ensemble (ENS, top) and the reduced ensemble (RENS, bottom). The reduction preserves both the mean and the spread. From the CETEMPS ensemble work (PROMETEO project).*

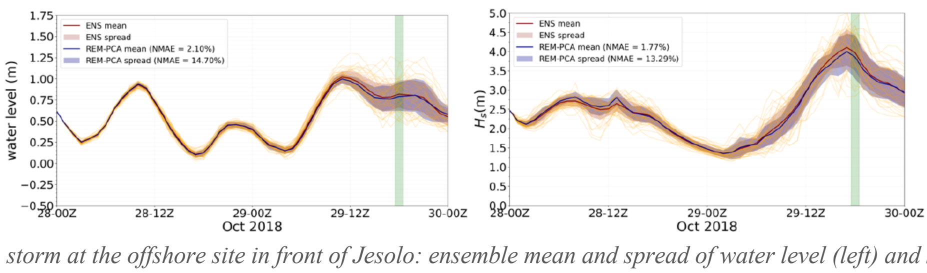

Figure 15. *Vaia storm at the offshore site in front of Jesolo: ensemble mean and spread of water level (left) and significant wave height (right) from the full ensemble (ENS, red) and the reduced ensemble (RENS, blue; NMAE relative to ENS in the legend); individual members in orange, event peak shaded green. From the CETEMPS ensemble work (PROMETEO project).*

6.6 Coupled atmosphere-ocean-wave modelling and the 2026 air-sea attribution campaign

The distinctive objective of ECHOES is to quantify the role of the ocean and of the sea state in Mediterranean cyclones. Two coupled suites are being deployed: the structured COAWST framework (WRF-ROMS-WW3), with first fully coupled tests performed for Daniel and Ianos, and the unstructured SHYFEM-WW3 suite introduced in Section 6.1 (Mediterranean grid, ≈ 12 km offshore to ≈ 500 m at the coast), forced by the WRF reanalysis. A direct downstream application is the Ensemble-Based Coastal Flooding Index (CFI; Favaretto et al., 2026), which links the total sea level at the beach computed by an atmosphere-ocean-wave chain that includes nearshore wave processes to the geometry of local coastal defences, and uses the ensemble (and its reduced counterpart, Section 6.5) to deliver probabilistic early-warning information. The framework has been demonstrated on the Jesolo pilot site (Figure 16) for the Vaia (2018) and Detlef (2019) storms, showing that the reduced ensemble preserves the early-warning signal because it is controlled by the presence of distinct relevant scenarios rather than by their relative frequency.

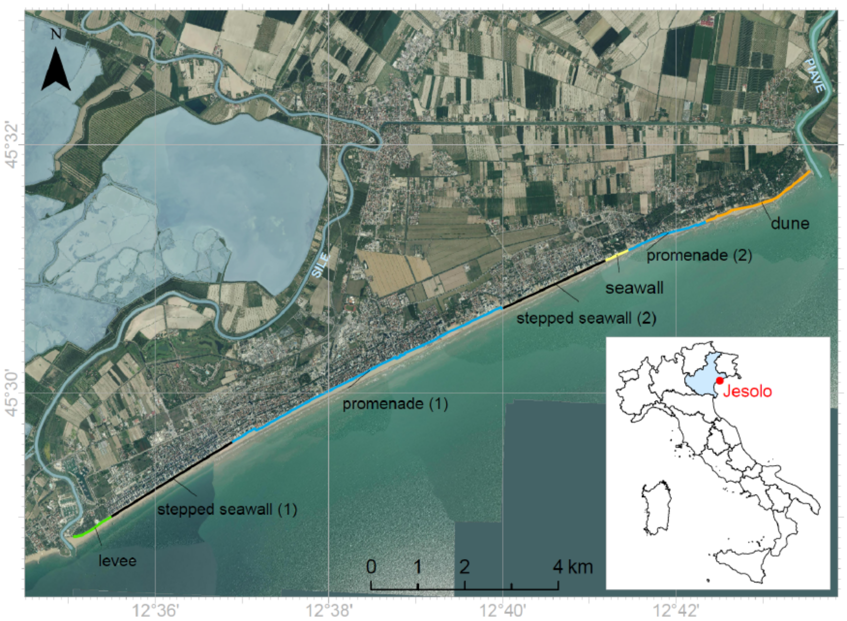

Figure 16. *Pilot site of the Ensemble-Based Coastal Flooding Index: the low-lying urbanised Jesolo littoral (Northern Adriatic), with the coastal-defence structures protecting the shoreline highlighted by colour. From Favaretto et al. (2026, egusphere-2026-2285).*

The probabilistic skill of the CFI follows directly from the ensemble. For each defence structure the index is computed from two hourly total sea levels a run-up-dominated level and a set-up/overflow-dominated level compared with the structure crest and berm, and it takes four ordinal values from no flooding to inland flooding by overflow. Driving the chain with the full ensemble (50 members), the reduced ensemble (15 members) and a single deterministic run shows that the reduced ensemble closely reproduces the probability distribution of the four CFI classes obtained from the full ensemble across the seven Jesolo defence structures, preserving the relative weight of overtopping versus overflow, whereas the deterministic run collapses to a single class and discards the uncertainty information (Figure 17). This is precisely the probabilistic, impact-oriented early-warning capability that ECHOES aims to deliver operationally, and it is made affordable by the ensemble-reduction strategy of Section 6.5.

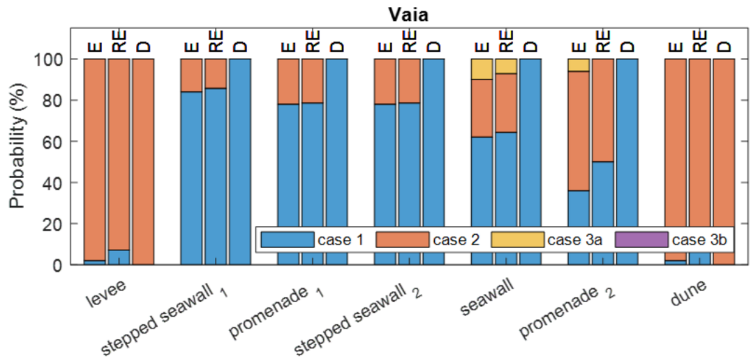

Figure 17. *Probability of the four Coastal-Flooding-Index classes for seven coastal-defence structures along the Jesolo coastline during Vaia, obtained with the full ensemble (E), the reduced ensemble (RE) and the deterministic run (D); cases 3a and 3b correspond to overtopping and overflow. From Favaretto et al. (2026; PROMETEO project).*

Two exceptional 2026 storms Storm Harry, an explosive cyclogenesis over the Ionian Sea (January 2026), and Medicane Jolina, a Tropical-Like Cyclone (March 2026) offered a unique, scientifically urgent opportunity to study, while observations are still fresh, how the ocean controls intensity, structure and predictability. Both were combined wind-and-wave extremes with severe coastal impact. They are the subject of the supplementary 2026 campaign (detailed in the resource-justification section below): for each event, convection-permitting WRF (and companion ICON members) on a two-way-nested 3 km/1 km grid are run as a multi-physics/multi-model ensemble, complemented by ocean-sensitivity experiments (SST modified by ±1 to ±4 °C, observed SST/Ocean-Heat-Content anomalies, and ocean-mixed-layer-depth experiments through the WRF slab-ocean scheme), a Pseudo-Global-Warming attribution block (CMIP6-derived thermodynamic deltas for three future scenarios), and a standalone WW3/SWAN wave block forced by every atmospheric member.

Figure 18 shows the HIMPACT-tracked trajectories of the Jolina ensemble: the members reproduce the southeastward path and the characteristic loop over the central Mediterranean, with a track spread that is strongly modulated by the prescribed ocean configuration and by the use of observational nudging (FDDA) versus free runs. The control of the ocean on the system is made explicit in Figure 19, which reports the basin-mean and the maximum total surface heat flux (sensible plus latent, HFX+LH) across the ensemble: the flux envelope is very wide the basin mean spans roughly 65 to 540 W m^{-2} and the maximum reaches ≈ 1450 W m^{-2} and the warm-SST/suppressed-mixed-layer members systematically sustain the highest fluxes. This quantifies, for a real 2026 medicane, the air-sea energy supply that the ECHOES coupled hindcasts are designed to represent, and provides the present-climate baseline against which the PGW future-scenario members are compared.

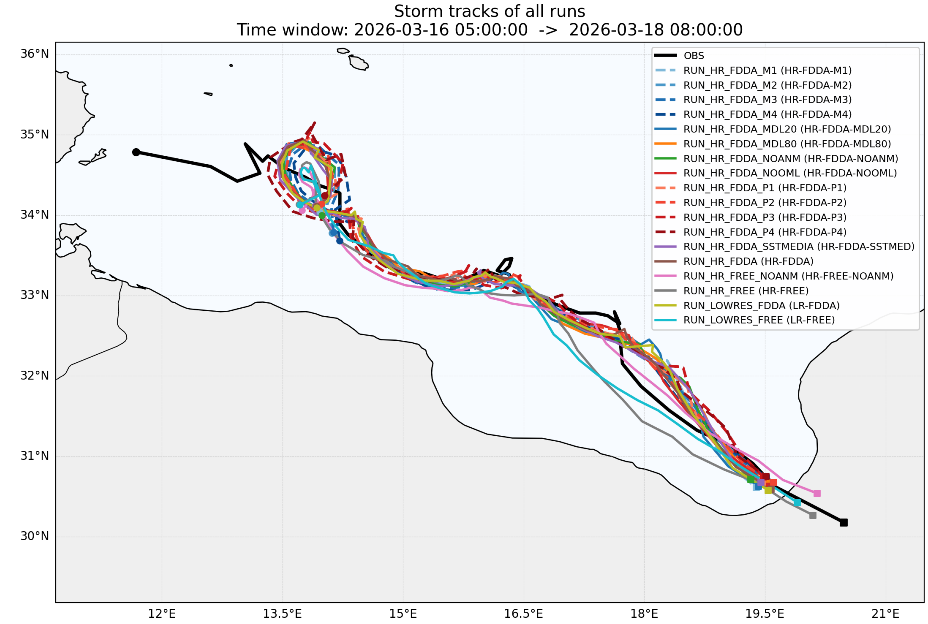

Figure 18. *HIMPACT-tracked trajectories of the Medicane Jolina multi-physics/ocean-sensitivity ensemble (16-18 March 2026) against the observed track (black). Members differ in resolution (HR/LOWRES), observational nudging (FDDA/FREE), ocean-mixed-layer depth, slab-ocean settings and SST perturbations. ECHOES 2026 supplementary campaign.*

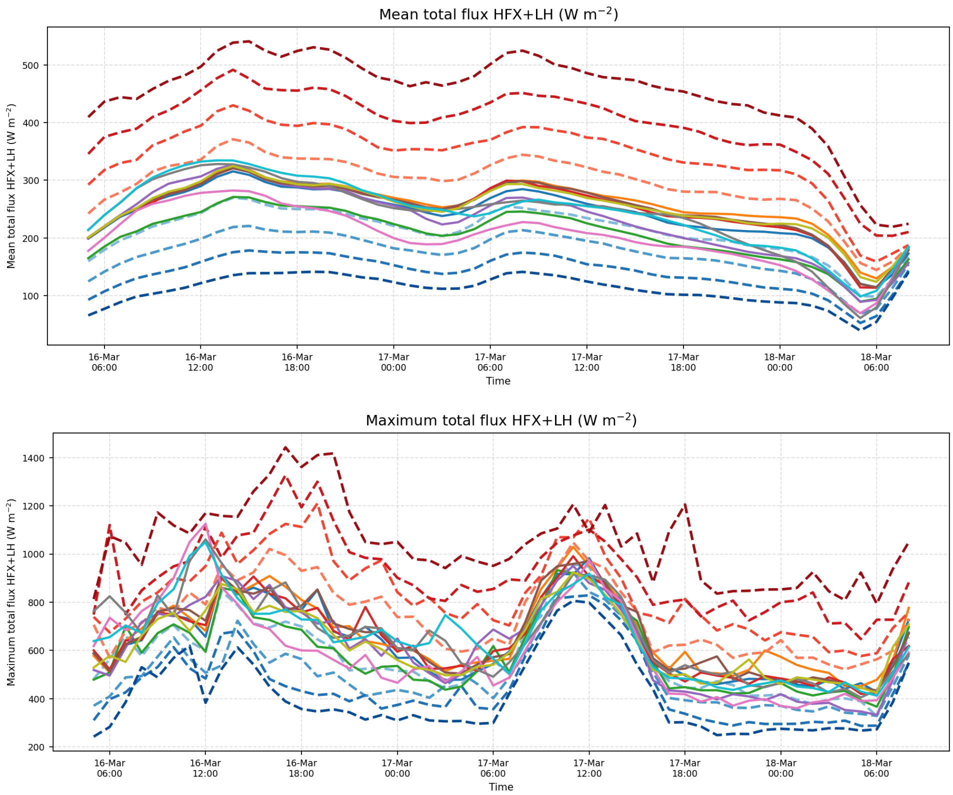

Figure 19. *Time series of the basin-mean (top) and maximum (bottom) total surface heat flux (HFX+LH) over the Jolina ensemble. The warm-SST/reduced-mixed-layer members (red, dashed) sustain systematically larger air-sea fluxes than the cold-ocean members (blue, dashed), illustrating the dominant control of the prescribed ocean state on the cyclone's energy supply. ECHOES 2026 supplementary campaign.*

The value of high-frequency, convection-permitting output for these coupled, rapidly evolving events is illustrated by the Neverin case of 16 April 2024, when a surface low over the Pó Valley triggered violent supercells over Veneto and Friuli Venezia Giulia, with bora gusts exceeding 120 km h^{-1}, giant hail (8-10 cm) and a sudden, sharp change of the sea state in the North Adriatic that caught small-vessel sailors unprepared. The event is a stringent test of the modelling chain: a WRF forecast with 5-minute output reproduces the observed fast and sharp increase of wind speed at the Acqua Alta Oceanographic Tower (AAOT) that the 1-hourly IFS output cannot resolve (Figure 20). For events prone to rapid development, an output frequency higher than hourly therefore translates directly into a better early warning at the end of the chain and the case also links the rapid-development and air-sea themes to the hail microphysics examined next, because the same Bora outbreak that destabilised the Adriatic sea state fed the supercells that produced the giant hail.

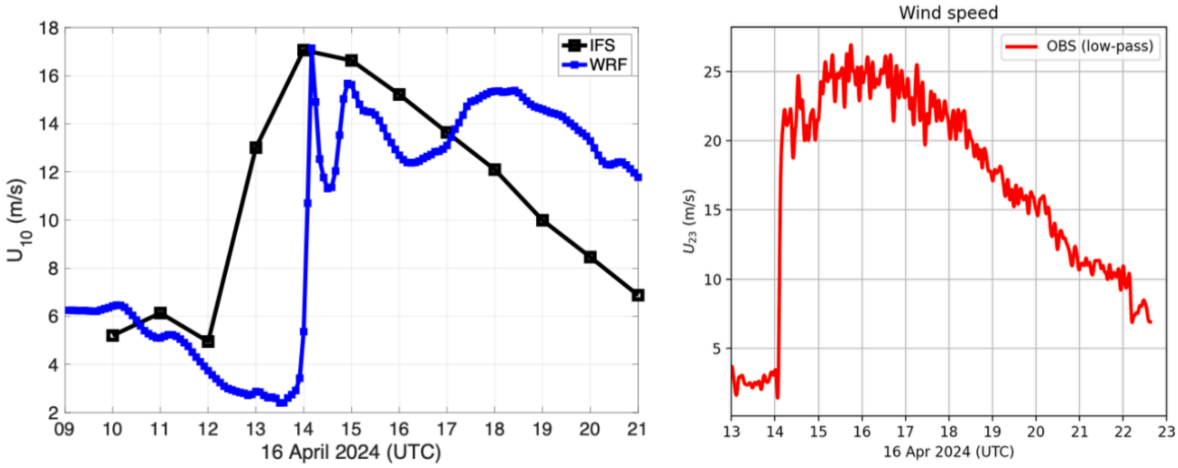

Figure 20. *Neverin event (16 April 2024): comparison between 1-hourly (IFS, black) and 5-minute (WRF, blue) forecast of wind speed at the Acqua Alta Oceanographic Tower (AAOT), left, and high-frequency (low-pass) observed wind speed at AAOT, right. The high-frequency WRF output captures the sharp wind increase missed by the hourly fields. From the shared ECHOES/PROMETEO framework (PROMETEO project).*

The same air-sea-interaction theme is explored at the microphysical end of the problem through the Pó Valley hail case of 26 July 2021 (Ricchi et al., 2026), in which a long-lived supercell produced hailstones larger than 8 cm. Two WRF + HAILCAST simulations with double-moment microphysics contrast continental (C-CCN) and maritime (M-CCN) cloud-condensation-nuclei loadings the maritime spectrum representing the sea-spray-loaded marine air mass whose aerosol burden is itself modulated by the ocean and the sea state. The two CCN regimes produce markedly different supercells (Figure 21): the maritime case develops a stronger, tighter, straight updraft (peak ≈ 40 vs ≈ 37 m s^{-1}) with faster forward propagation (≈ 83 vs ≈ 68 km h^{-1}) but a shorter lifetime, whereas the continental case delays warm-rain processes, develops a tilted updraft with a bounded weak-echo region and persists longer, travelling ≈ 150 km. This case study closes the conceptual loop of ECHOES from the ocean and the sea state, through sea-spray aerosol and cloud microphysics, to the dynamics and severity of the convective storm and motivates the explicit treatment of wave-modulated aerosol-microphysics coupling in the next phase of the project.

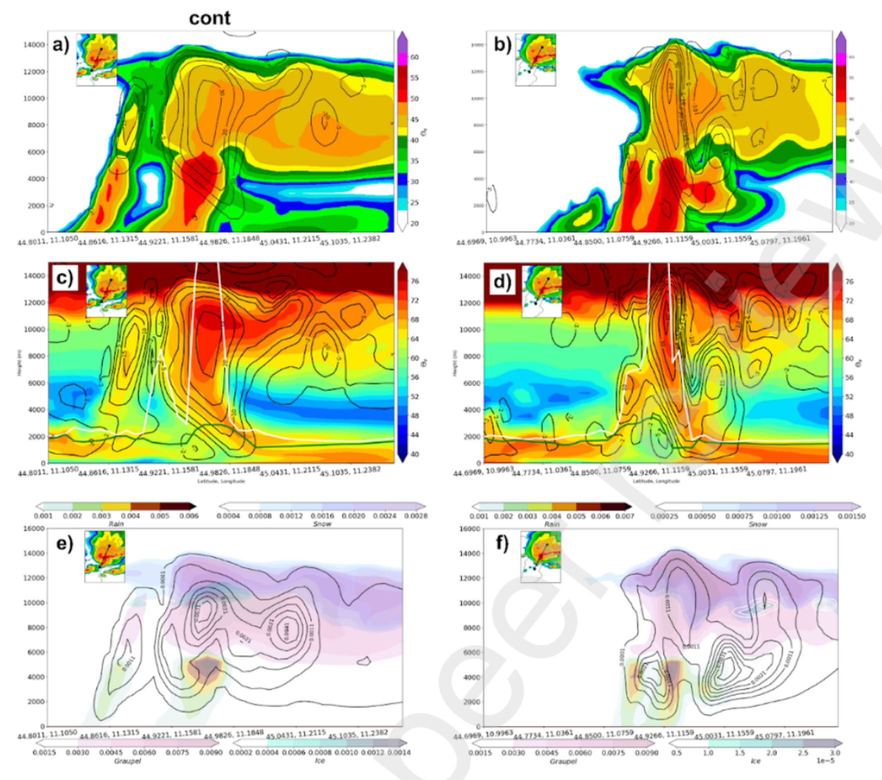

Figure 21. *Vertical cross-sections of the 26 July 2021 Pó Valley supercell for the continental (left, a/c/e) and maritime (right, b/d/f) CCN simulations: radar reflectivity and vertical velocity (a,b), equivalent potential temperature and vertical velocity with LCL/LFC (c,d), and hydrometeor type with hail content (e,f). The maritime CCN run yields a stronger, more vertical updraft. From Ricchi et al. (2026, SSRN 6270278).*

Justification of computing resources and request for 2027

7.1 Resources used in 2026 and the supplementary allocation

As of 29 June 2026 the project had consumed 26,803,240 SBU, i.e. 50.6% of the 53,000,000 SBU available for the year, shared among four active users, and is on a trajectory to use the full allocation by year-end. This represents a decisive scale-up of production relative to 2025, when only 15.46 M SBU were billed during the configuration-dominated first year. The 2026 consumption has been spent on (i) the continuation of the long-term atmospheric reanalysis and its migration to the target 3 km convection-permitting configuration; (ii) the seven-member WRF/ICON Daniel suite and its diagnostics; (iii) the Qendresa assimilation experiments; (iv) HIMPACT validation runs; and (v) the Storm Harry and Medicane Jolina ensemble/ocean-sensitivity/PGW campaign, which is the activity covered by the supplementary allocation. The multi-decadal validation of the coupled chain and part of the ensemble-reduction work (Sections 6.1 and 6.5) were carried out within the connected national project PROMETEO on national HPC infrastructure and did not consume any ECHOES SBU; they nonetheless de-risk the 2027 event-study campaign described below, since the coupled modelling system to be exploited at very high resolution on ATOS is already validated at climatological scale.

The 50,000,000 SBU originally approved for 2026 in the project plan had been reduced to a 38,000,000 SBU baseline. Because the reduced baseline left no room for the scientifically urgent Harry/Jolina study an opportunity that exists only while the events are recent and the observations complete a supplementary request of 15,000,000 SBU was submitted and approved in June 2026, restoring the 2026 allocation to 53,000,000 SBU. The supplementary campaign is strictly additional to the already-planned 2026 activities and comprises 204 production runs, costed from SBU consumptions measured within ECHOES on the ATOS HPCF (3 km Mediterranean WRF ≈ 420 SBU per simulated hour on 512 cores; the two-way 1 km nest raises this to ≈ 1,300 SBU per simulated hour, i.e. ≈ 125,000 SBU per 96-hour run; standalone WW3/SWAN wave runs ≈ 10,000 SBU each).

Supplementary campaign experiment block	Runs	SBU/run	Total SBU
(i) Multi-physics sensitivity (12 × 2 events)	24	125,000	3,000,000
(ii) Multi-physics/multi-model ensemble (15 × 2)	30	125,000	3,750,000
(iii) SST ±1-4 °C, SST/OHC anomaly, mixed layer (12 × 2)	24	125,000	3,000,000
(iv) PGW: 3 scenarios × 4 members × 2 events	24	125,000	3,000,000
(v) WW3/SWAN wave runs forced by all members (i-iv)	102	10,000	1,020,000
Subtotal (204 production runs)	**204**		**13,770,000**
Pre-processing (WPS/ICON/wave grids, ≈ 4%)			550,000
Contingency: restarts, crashes, re-runs (≈ 5%)			680,000
Supplementary total (approved June 2026)			**15,000,000**

No additional storage, GPU or EWC resources are required for the supplementary campaign: post-processing, extreme-value/return-period analysis and configuration tuning are carried out on local UNIVAQ/CETEMPS servers, and the 20 TB data allocation remains sufficient.

7.2 Request for 2027

For 2027 the project requests the full HPCF allocation foreseen in the original three-year plan: 50,000,000 SBU, together with the existing 20,000 GB (20 TB) of data storage. With the long-term reanalysis produced and validated in 2025-2026 (Sections 6.1 and 6.5), the 2027 allocation is devoted to the core scientific objective of ECHOES: a systematic, process-level study of the principal high-impact events of the Mediterranean, selected from the produced reanalyses. Four event families are targeted Mediterranean tropical-like cyclones (medicanes), rapid (explosive) cyclogenesis, wind-wave storms, and heatwaves (atmospheric and marine) and each selected event is investigated with a common, demanding methodology: fully coupled atmosphere-ocean-wave modelling, very high (km-scale) horizontal resolution, and dedicated SST-impact/ocean-role experiments (SST perturbations, observed SST/Ocean-Heat-Content anomalies and ocean-mixed-layer experiments) that quantify the air-sea control demonstrated for Jolina in Section 6.6. To make probabilistic information affordable at this resolution, km-scale ensembles are run only for a reduced, relevant set of representative members obtained with the ensemble-reduction method of Section 6.5. The plan is anchored on a catalogue of at least ten of the principal medicanes documented in the literature and contained in the reanalysis period Celeno (January 1995), the Balearic tropical-like cyclone (October 1996), the Apulia case (September 2006), Rolf (November 2011), Qendresa (November 2014), Numa (November 2017), Zorbas (September 2018), Ianos (September 2020, the most intense, reaching Category 2), Apollo (October 2021) and Daniel (September 2023) extending to the recent Jolina (March 2026) already analysed under ECHOES; analogous sets are selected for rapid cyclogenesis (e.g. Storm Harry, January 2026), wind-wave storms (e.g. Saint Agatha 2015, Vaia 2018, Detlef 2019) and the major Mediterranean heatwaves of the reanalysis period. The plan is completed by a targeted, fully coupled high-resolution reanalysis of the selected years that contain the densest clustering of these extremes, which provides the consistent coupled context for the event studies. Costs are scaled from the consumptions measured in 2026 on the ATOS HPCF: a fully coupled, km-scale (1 km nest) atmosphere-ocean-wave member costs ≈ 150,000 SBU per ≈ 96-hour event, so a 15-member reduced ensemble per event costs ≈ 2.25 M SBU. The indicative breakdown below sums to the requested 50 M SBU; the optimised set-ups validated in 2025-2026 (best-performing physics, the shallow-convection bridge, and the drag and slab-ocean settings) reduce the per-run cost and de-risk this plan.

Planned 2027 activity	Indicative SBU
Medicane catalogue (≥ 10 events): fully coupled, very-high-resolution simulations with SST-impact/ocean-role sensitivity	12,000,000
km-scale ensemble reduction (≈ 15 representative members) on the highest-impact medicanes and cyclogenesis cases, fully coupled	13,000,000
Rapid (explosive) cyclogenesis and wind-wave storm cases: coupled high-resolution runs with ocean/wave sensitivity	9,000,000
Heatwave cases (atmospheric/marine): ocean-coupled high-resolution sensitivity (SST, mixed layer, OHC)	4,000,000
Targeted coupled high-resolution reanalysis of selected extreme-event-rich years	8,000,000
Pre-processing (≈ 4%) and contingency/restarts (≈ 5%)	4,000,000
Total requested for 2027	**50,000,000**

Data storage for 2027 is requested unchanged at 20,000 GB (20 TB); it remains sufficient under the continuous offload-and-purge policy. No GPU or EWC resources are requested.

In summary, the project has corrected the slow first-year ramp-up: 2026 is on track to fully use a substantially larger allocation, a high-value attribution campaign on two landmark 2026 storms has been added and funded, and the validated coupled modelling chain (Section 6) now enables the core scientific exploitation planned for 2027. The requested 50 M SBU and 20 TB are the originally approved figures and are necessary to deliver a systematic, process-level study of the principal Mediterranean high-impact events at least ten medicanes together with rapid-cyclogenesis, wind-wave-storm and heatwave cases selected from the produced reanalyses investigated with fully coupled, very-high-resolution, ensemble-reduced simulations focused on the SST impact and the role of the ocean, and complemented by a targeted coupled reanalysis of the most extreme-event-rich years. The resulting event catalogue and high-resolution coupled datasets will be released as open-access products for climatological, risk-assessment and machine-learning applications.