REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	ITALY
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Project Title:	Exploiting Coupled, High-resolution modelling to simulate severe mediterranean cyclOgenesES (ECHOES)..

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** itricc	
Starting year: A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES [X]	NO [ ]

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	60000000	50000000	50000000
Accumulated data storage (total archive volume)[2]	[GB]	20000	20000	20000

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	0	0	0
Total memory	[GB]	0	0	0
Storage	[GB]	0	0	0
Number of vGPUs[3]	[#]	0	0	0

Continue overleaf.

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Extended abstract

Motivation

The study of meteorological and marine events, sometimes still difficult to predict and to simulate in reforecasts and reanalyses, plays a crucial role in satisfying different societal needs ranging from the pure advancement of knowledge to applications like early-warning and climate change adaptation (WMO, 2023). The simulation of the atmosphere dynamics and its interaction with the marine component through the air-sea interface is even more challenging in extreme (e.g., windstorm) conditions and in complex geographical areas, like the Mediterranean region, and in coastal and transitional areas (Cavaleri et al., 2018; Cavaleri et al., 2024, Chelton et al 2007, O'Neill et al 2010). Indeed, the Mediterranean Sea, an enclosed basin surrounded by orographic systems, is a major hot spot of extreme weather/sea events (increasing their frequency and intensity due to global warming more than how is generally happening in the world) and given the strong anthropization along its coastline (and its relative increase), the need for better and better skills in simulating extreme meteo-marine Mediterranean events, as cyclones like the so-called Medicanes (Mediterranean Tropical-Like Cyclones, TLC) and Explosive Cyclogeneses (EC), is clearly evident. This can be achieved by means of state-of-the art high resolution (convection permitting) coupled numerical modelling, taking into account the Ocean Heat Contents, momentum, energy and heat/moisture fluxes that contribute to triggering the generation of severe weather events at sea and driving their evolution till the highly inhabited lands where their impact is stronger (Olabarrieta et al 2012, Ricchi et al 2016, Ricchi et al 2017, Ricchi et al 2021, Rizza et al 2018) . To complement the state-of-the-art numerical prediction of the atmosphere and the sea state and dynamics, numerous technologies are gaining consensus: from 'Digital-Twin' approaches to the massive application of Machine Learning (ML) techniques. All these approaches are motivated by the existence of massive amounts of data produced by observations and numerical models. Not all of them develop at the same speed and with the same degree of performance. The numerical models on which digital-twins apps are based do not always have a daily predictability that is constant in time and homogeneous in space. Moreover, they often fail to adequately represent wide ranges of atmospheric events (e.g., severe storms), partly due to the use of numerical parameterisations calibrated to certain intensity ranges. While producing a lot of data is crucial for the training of ML applications, it may prove erroneous to produce data with low predictability and representativeness, particularly at sea, where observations are scarce and often underestimated.

Objectives

Building upon this rationale, the ECHOES special project we propose here (Exploiting Coupled, High-resolution modelling to simulate severe mediterranean cyclOgenesES) aims to address the need for accurate and skilful simulation of extreme weather-marine events in the Mediterranean region by:

1. reforecasting a selection of 10 severe cyclones (with estimated 10m wind greater than 25 m/s) that developed in the Mediterranean basin and impacted the countries in the region in the past 30 years by means of uncoupled and fully coupled short-term simulations of atmospheric, ocean and wave components, with the aim of (i) assessing benefits and costs of coupled and uncoupled simulations, and (ii) optimizing the coupled modelling set-up, e.g., in terms of air-sea fluxes parameterizations (more in the “Methodology” section). For the verification of the model skills and event predictability we will target marine (e.g., storm surge, waves) and atmosphere (e.g., precipitation, wind; also, on the land) output variables

(See Table 1 of Events in the Methodology section for the Explosive Cyclogeneses and Tropical-Like Cyclones);

2. reforecasting the state of the atmosphere in the 30-year period including the simulated events, using the optimized modelling set-up for the atmospheric component.
3. hindcasting the ocean-wave state in the 30-year period including the simulated events, using the optimized modelling set-up for the coupled ocean-wave components, forced by the atmospheric reforecasting; for the ocean-wave simulations we will use and compare the results of two different modelling suites employing two different modelling approaches for the spatial discretization (i.e., a mosaic of nested structured grids on the one hand and unstructured grid on the other) to highly resolve the coastal seas.
4. producing 30-year datasets of atmospheric and ocean-wave variables for climatological studies tailored to the extreme events in the Mediterranean region and for Machine Learning purposes. Indeed, the use of numerical models is the starting point for producing large datasets for Machine Learning model training, which require increasingly higher resolution data to be able to interpret and reproduce phenomena at sub-grid scales, also covering the extreme events regime.

ECHOES is the partial continuation of the ASIM-CPL special project (Air-Sea Interactions on the Mediterranean basin, using 'atmosphere-ocean-waves' CouPLed numerical models, SPitricc), that was aimed at investigating the effect of atmosphere-wave-sea interactions on the Mediterranean basin, with the aid of coupled numerical models at different time scales.

Methodology

In ECHOES, to simulate the state and dynamics of the atmosphere we will use the atmospheric model WRF (Weather Research and Forecasting system; Skamarock et al. 2008), in 4.6 version, contained in COAWST (Coupled Atmosphere Ocean Wave Sediment Transport system, Warner et al 2010, which provides the option of coupling WRF with ROMS and WW3 models, without modifying the WRF model apart from adding parameterisation and coupling schemes) . WRF is a state-of-the-art numerical model for weather simulation solving the fully compressible, nonhydrostatic Euler equations. The WRF numerical model will be implemented on a 3 km horizontal resolution grid, size 1446x736 grid point, covering the entire Mediterranean Sea basin and the water basins of greater methodological and dynamic impact, adjacent to the coastal area (Figure 1). The calculation grid will be based on a USGS 30s resolution topography, CORINE 2018 sub-km resolution land use dataset. The model will be run with 70 hybrid vertical layers, with the first layer at 15 metres above ground level, in order to represent the first Boundary Layer with greater consistency, and to make the numerical representation of the ground level and the first modelling layer consistent. The WRF model configuration is based on Ricchi et al (2021) and tests carried out previously on this grid (Figure 1) and on some MEDICANEs and EC, including some of the ones proposed in Table 1: explicit cumulation scheme, 45 vertical levels with the first level located 15 meters above the ground, Mellor Yamada Janic (Janich et al 1994) Planetary Boundary Layer scheme, RRTMG radiation scheme (Mlawer et al 1997) and the activation of the oceanic slab (1D) model, which calculates, depending on the interactions with the atmosphere, and the prescribed depth, of the Ocean Mixed Layer, the SST variation. Mixed Layer Depth and Sea Surface Temperature are inserted, in each run, starting from the CMEMS dataset (CMEMS in bibliography). The microphysics scheme will be based on Milbrandt and Yau, 2005, double-moment 7 class of hydrometeors. The scheme will also implement the estimation of hail diameter (Hailcast module) and lightning strikes.

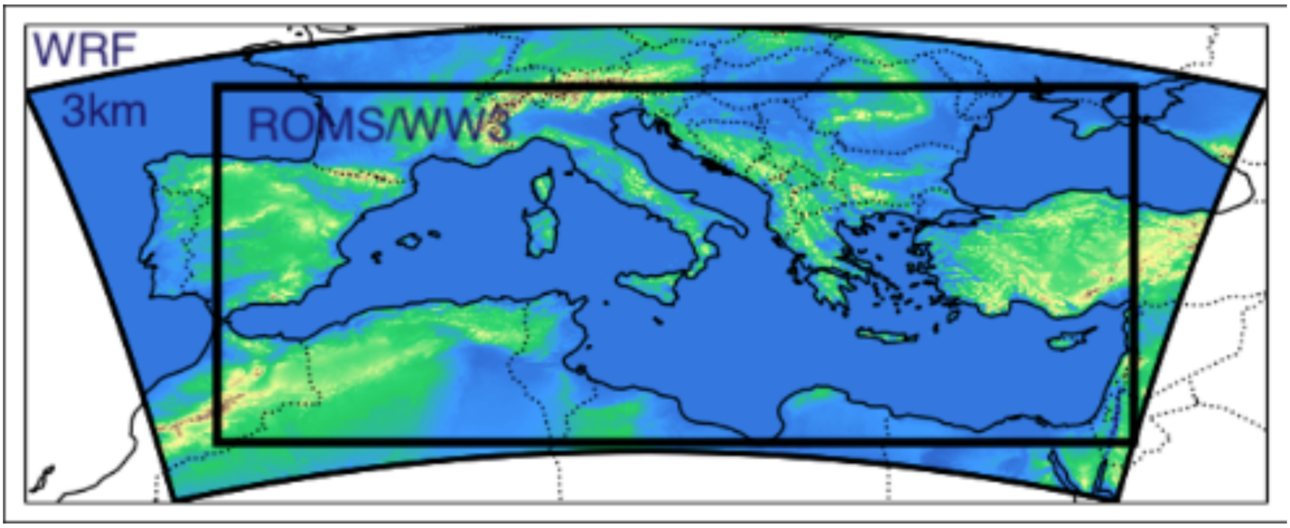

Figure 1. Numerical grids for the WRF models (3 km) ROMS and WW3

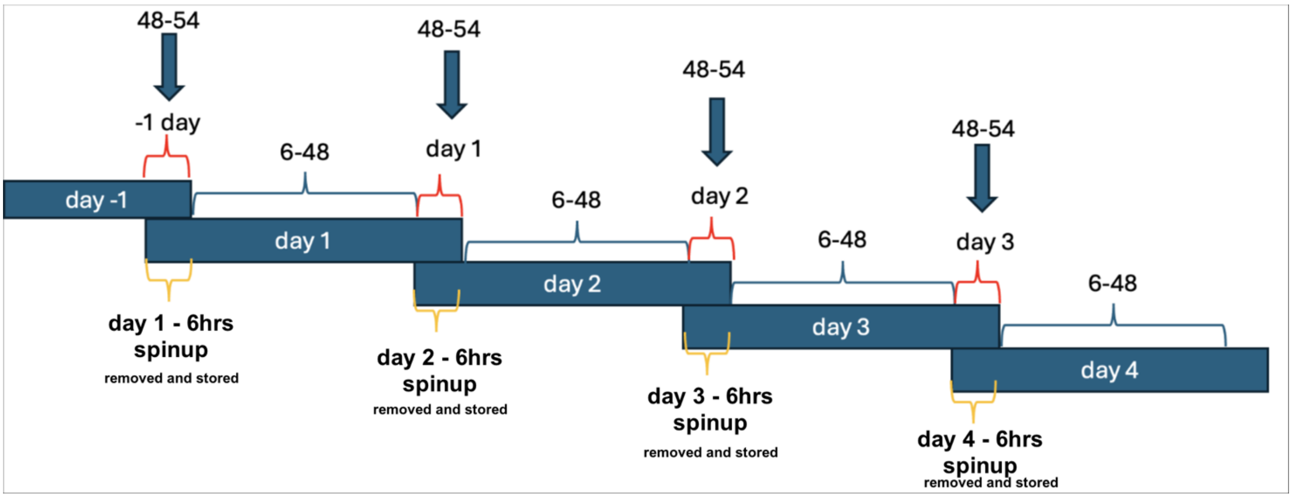

Figure 2 - Re-forecast strategy for WRF long-term simulations.

The WRF model simulations will all be performed in re-forecast mode with initial and boundary condition provided by ECMWF-IFS 9 km. The reforecast simulations will see 54-hour runs, initialized at 00UTC. To limit the impact of the model spinup, the first 6 hrs of simulation will be eliminated, and replaced by the last 6 hrs of the previous simulation (the first 6 hours will not be removed, but just not considered in these statistics). In this way, performance and results are optimized (Figure 2).

To simulate the state and dynamics of the ocean and wave components we will use two numerical modelling suites. The first is the COAWST (Coupled Ocean Atmosphere Waves Sediment Transport model; Waner et al., 2010) modelling framework coupling the atmospheric model WRF, the oceanic model ROMS (Regional Oceanographic Modelling System; Shchepetkin et al., 2005), and the wave model WW3 (WAVEWATCHIII; WW3DG, 2019). ROMS and WW3 will use the same 3-km horizontal resolution structured curvilinear grid covering the entire Mediterranean Sea, with an open boundary at the Gibraltar Strait (Figure 1). In ECHOES, we target the marine surface variables only, thus ROMS will be used to solve the 2D Reynolds-averaged and depth-averaged Navier–Stokes equations, whereas WW3 will provide a phase-averaged description of the generation, propagation and dissipation of the sea state by dividing the spectral domain into 32 logarithmically-spaced frequencies and 36 directions.

The second modelling suite will couple the SHYFEM (Shallow water HYdrodynamic Finite Element Model; Umgiesser et al., 2004) model and WW3. SHYFEM will be used to solve the 2D Reynolds-averaged and depth-averaged Navier–Stokes equations using the finite element method on unstructured meshes, which are particularly suitable for areas with complex geometry and bathymetry, such as jagged coasts and islands. SHYFEM and WW3 will use the same unstructured grid with 163,000 triangular elements with horizontal resolution ranging from 8 km in the open sea to 500 m along the North Adriatic Sea coast (Figure 3 and 4).

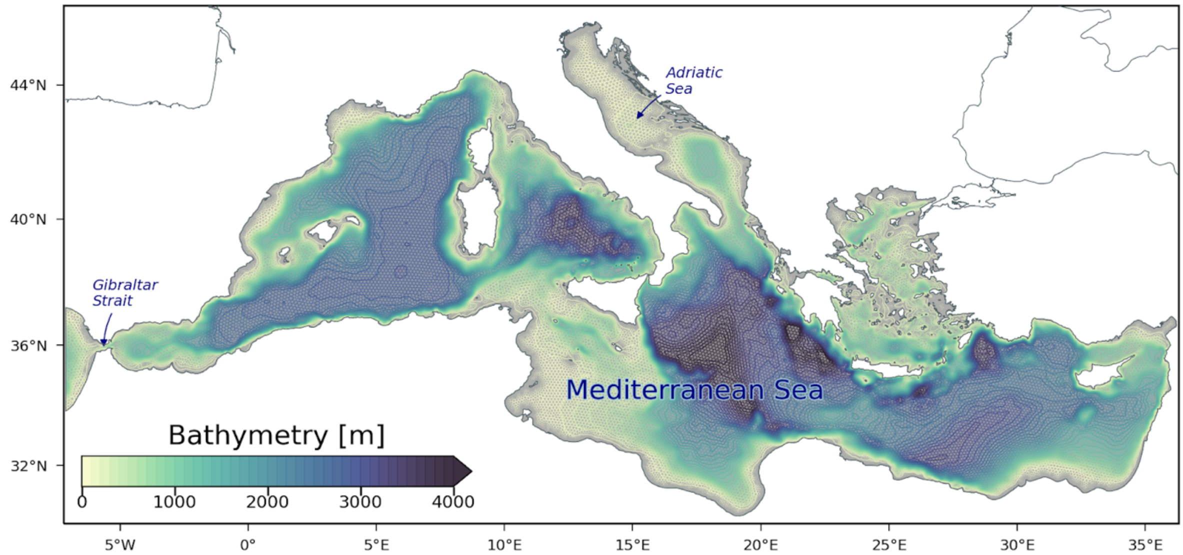

Figure 3 – SHYFEM-WW3 domain and unstructured computational grid.

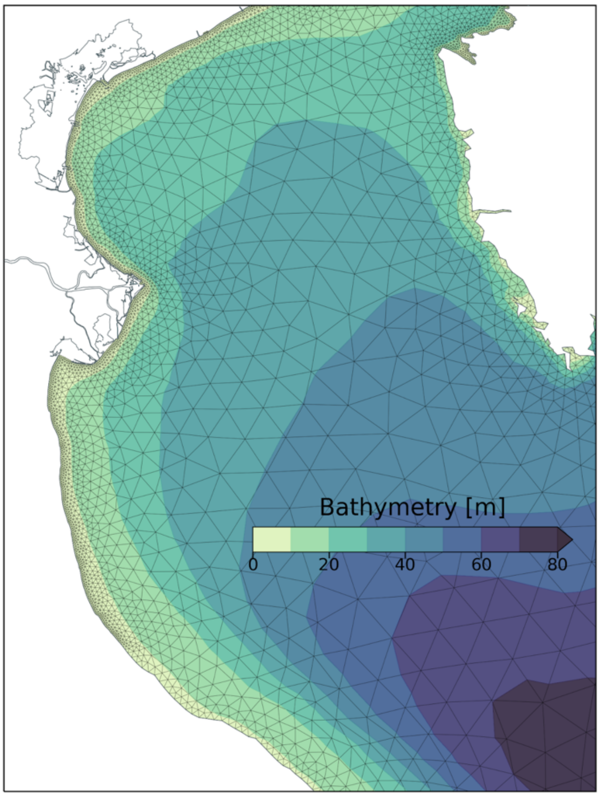

Figure 4 – Details of the SHYFEM-WW3 unstructured computational grid in the North Adriatic Sea. Horizontal resolution ranges from 8 km in the open sea to 500 m along the North Adriatic Sea coast.

The fully coupled runs will see the implementation of the COAWST system, in "different grid" mode in which the numerical grids of the 3 models are coupled based on weight matrices through which the framework (using the MCT toolkit) exchanges the variables between the models (Figure 5). The resolution of the grids will be at least the same (3 km for ROMS and WW3 coupled) but geographically adapted to local needs, but we do not rule out local grid refinement or nesting, as in the northern Adriatic area. Coupled simulations will be performed according to the default scheme for surface roughness parameterization (Charnock et al 1956), Drennan (Drennan et al 2003), Oost (Oost et al 2002) and Taylor-Yelland (Taylor et al 2001). Moreover, we will explore the potential implementation of the semiempirical reduction of the Charnock parameter in high-wind regimes implemented in the CY47R1 version of IFS at ECMWF. The simulations will be performed on the 10 cases selected and shown in Table 1. The ROMS model will see the use of a GLS mixing model (Warner et al 2010), 75 vertical levels, open boundaries in Gibraltar (derived from the CMEMS, Clementi et al 2017 model), river inputs derived from climatology's and tidal TOPEX dataset.

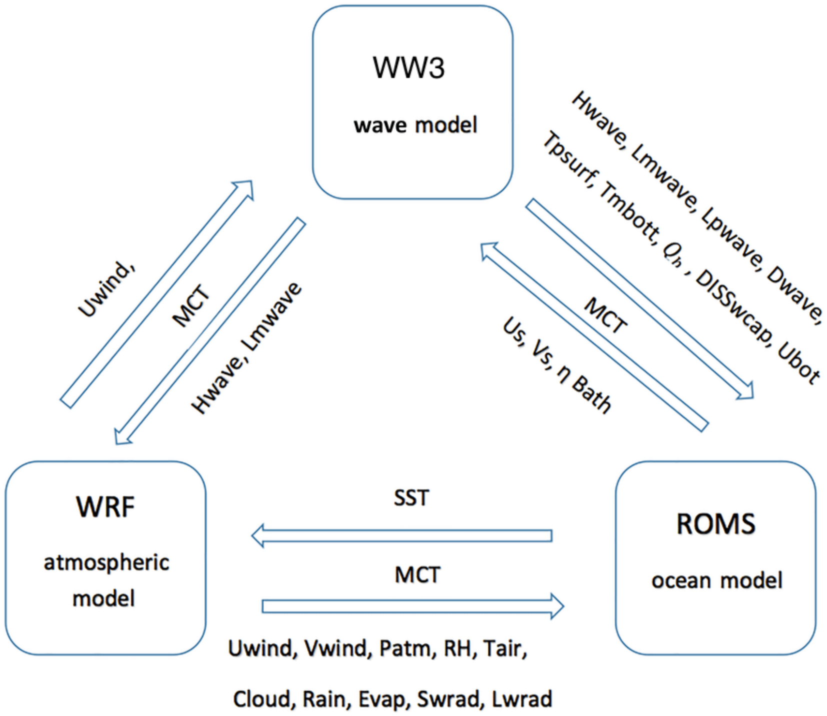

Figure 5. COAWST framework and data transfer between models, via MCT, in coupled simulation as WRF+ROMS+WW3 and ocean coupling re-forecast ROMS+WW3 (same for SHYFEM-WW3).

TLC (name and date)		**EC (date and DR)**	
Rolf	2011/11/04-09	06/02/2012	1.66
Numa	2017/11/16-19	16/03/2003	1.56
Zorbas	2018/09/27-30	22/01/2004	1.57
Ianos	2020/09/15-21	13/12/2005	1.57
Daniel	2023/09/04-11	29/10/2018	1.41

Table 1. The table represents the 10 case studies of the most intense cyclogenesis occurring over the Mediterranean Sea basin in the 30-year study period (1994-2023), with estimated winds greater than 25 m/s. TLC = Tropical-Like Cyclones; EC = Explosive Cyclone; DR = Deepening Rate (expressed in Bergeron)

Workplan

The simulations we plan to perform in ECHOES are:

- short-term (3 to 5 days) simulations of severe/extreme cyclones occurred in the Mediterranean region, including 5 Medicanes and 5 explosive cyclogeneses, using the uncoupled and coupled approaches. This activity comprises the optimization of the model set-up and of the coupling strategy. We will consider events with estimated 10m wind speed larger than 25 m/s (Table 1).
- 1 long-term reforecast of the atmosphere state and dynamics in the 1994-2023 period using WRF, configured according to the outcomes of the short-term simulations. The reforecast is composed of 54-hour simulations, overlapped of 6 hours at the end of the simulation, with the start of the next simulation (Figure 2). This allows you to use the last six hours of the simulation, instead of the first 6 hours of the next simulation, which represents the spinup period.
- 1 long-term hindcast of the ocean and wave state and dynamics in the 1994-2023 period, using ROMS-WW3, configured according to the outcomes of the short-term simulations and forced by the atmospheric reforecast fields.
- 1 long-term hindcast of the ocean and wave state and dynamics in the 1994-2023 period, using SHYFEM-WW3, configured according to the outcomes of the short-term simulations and forced by the atmospheric reforecast fields.

Therefore, the workplan is the following:

1. Short-term simulation of the events in Table 1: numerical simulation of different modelling setups and implementation of the best setup (YEAR 1)
2. optimisation of performance and computing resources (YEAR 1)
3. re-forecast of 30-year long period with WRF (YEAR 1-2-3)
4. hindcast of 30-year long period with ocean-wave Coupled models (ROMS+WW3 and SHYFEM+WW3) forced by WRF re-forecast simulations (YEAR 1-2-3)

Expected results

The main outcome of ECHOES is the high-resolution atmospheric and marine datasets of the extreme Mediterranean cyclones (short-term) and of the 30-year long period entailing them (long-term), with multi-model approaches for oceanic hindcasts (ROMS-WW3 and SHYFEM-WW3). Indeed, by exploiting ECMWF computational resources, ECHOES is expected to build datasets that would be otherwise difficult to produce as they feature very high-resolution (up to 500 m along coastlines) of three components of the Earth system (atmosphere, ocean and wave; one- and two-way coupled), on a large spatial domain and over three decades.

Given the effort to produce them and the value of the datasets themselves, the selected atmosphere, ocean and wave variables from the datasets produced within ECHOES will be made available to the public, through open-access repositories, after an embargo period of 12 months after their validation.

ECHOES produced and distributed data will allow to train ML models for the characterisation and prediction of the atmospheric, oceanic and wave conditions in the Mediterranean region. Among the variables produced by the ECHOES models, atmospheric variables including hail, hail size and lightning strike, oceanic variables like the storm surge and wave variables like the expected maximum crest and wave height in sea states will be of particular interest, for the socio-economic impact they can have in, for instance, decision-making processes.

Beside these, the implementation of coupled multi-model and multi-physics approach simulations for selected TLC and EC events, at high resolution (convection permitting) with tests of drag coefficient schemes and their impacts both on the atmosphere and in the ocean will provide a scientific contribution to the modeling of extreme weather/marine events.

In addition, the use of selected cases, their investigation with numerous numerical approaches of increasing complexity, the application of 30-year reforecast/hindcasts for atmosphere (uncopled) and ocean (coupled ocean-waves), will make a major scientific contribution to the analysis of extreme events at convection permitting scales, across different geographical scales.

Justification of the computer resources requests

The computational resources required for ECHOES will be used to perform the simulations with (i) the numerical model WRF in Case Selected Atmospherical approach (Uncopled, only WRF model), (ii) WRF in re-forecast approach (only WRF uncoupled) for 30 years, (iii) coupled WW3-ROMS and (iv) coupled WW3-SHYFEM model forced by WRF output for 30 years.

Simulations on the proposed calculation grids, and with the chosen parameterisations and numerical approaches, are very computationally demanding. During the previous ASIM-CPL project we have performed some event simulations with the same configuration of ECHOES simulations (IANOS, ROLF, DANIEL Medicanes and some Explosive Cyclogeneses, as VAIA), therefore we base our estimates on those simulations. For WRF:

- In detail, 1 hour simulated with the WRF uncopled model, using 512 CPUs (adaptable at dynamical necessity) on the ATOS HPC (ECMWF, on which we request the application of this special project), consuming 420 SBUs. A 54-hour simulation consumes about 122.680 SBUs, which for one year of simulation (following our approach, where 1st 6hr are removed for spinup) is about 4.01 mln SBUs and 30 years 122.5 mln SBUs.
- The runs of 10 selected cyclones will consist of uncoupled simulations (on average cyclones of 4 days duration, 18-20000 SBU per cyclone).
- The same cyclones will be simulated with the coupled model, in 4 configurations (4 Cd drag coefficient parameterisations such as Charnock-IFS implementation, Drennan, Oost, Taylor-Yelland). Each coupled run uses approximately 50-60000 SBUs. In total, this part of the work uses approximately 2.5 million SBUs.
- The preprocessing of the WRF model is carried out before each run (for all proposed applications) and uses about 5% of the required resources for a total of about (7 mln SBUs).

The coupled Ocean-Wave runs (ROMS-WW3, SHYFEM-WW3) consume an average of 100 SBUs per simulated hour for an approximate total of about 29-30mln SBUs. Finally:

- stabilisation of calculation grids and model configuration is carried out locally, on our servers.
- post processing is carried out on our servers.
- A total of 160 mln SBU is required over 3 years, distributed according to the scheme outlined above (60 mln the first year; 50 mln the second year; 50 mln the third year).
- A tolerance margin for reboots, crashes, local tuning, in particularly extreme events, which could consume SBUs, is included in these estimates).

As far as storage is concerned, we estimate the need for about 20TB of continuous space (20TB fixed for the 3 years), continuously transferring data to our storage base at UNIVAQ/CETEMPS.

Technical characteristics of the code to be used

The software involved in ECHOES are:

- WRF-ROMS-WW3 models, within the COAWST system;
- SHYFEM-WW3 models.

Compilation of the COAWST package does not require any additional support compared to the compilation of the WRF model. The requests are the same as for the other models. SHYFEM-WW3 will be installed in a container of Singularity.

The modules required are: Intel compiler, netcdf4, jasper, zlib, szip, intel mpi.

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