REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	Italy
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Project Title:	Exploring high resolution modelling of extreme convective events in the Mediterranean Region with gSAM model

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.	………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025-2027	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	20.000.000	20.000.000	20.000.000
Accumulated data storage (total archive volume)[2]	[GB]	50 TB	50 TB	50 TB

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

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special 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.

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Background and motivation

The Mediterranean Sea is susceptible to synoptic scale baroclinic cyclonic storms, which occasionally result in the formation of intense mesoscale vortices that bear resemblance to tropical cyclones. These storms are sustained by large enthalpy fluxes from the sea, as demonstrated by three-dimensional modelling experiments (Miglietta et al., 2014, Flaounas et al., 2022).

Despite the relative rarity of these phenomena during the calendar year (one to two per year at most), their presence demonstrates that when the air below a cut-off low is unusually cold and moist, the combination of the low temperature, the relative warmth of the ocean below, and the high relative humidity provides an ideal environment for hurricane development (Emanuel, 2005). This kind of extreme convective event provides an interesting case for the use of ensemble techniques, which revealed that 1) the initial condition altered the dynamic and thermodynamic coupling in the tropical cyclone's growth, and 2) the convection uncertainty could explain the spread of the ensemble experiments (Saraceni et al., 2023).

Furthermore, The Mediterranean is particularly affected by convective extreme weather events, that are not associated with cyclonic circulation (Ducrocq et al., 2008). The occurrence of these extreme events can be explained by favorable meteorological conditions, including synoptic and mesoscale weather features, topography and the proximity of the Mediterranean Sea. The combination of these ingredients leads to the formation of slowly moving Mesoscale Convective Systems (MCSs), which can explain the exceptional hourly rainfall (Caillaud et al. 2024). This second type of event is taken into consideration, given the role of convective organization in their development. The organization of convection is driven by instability processes arising from both anomalous Mediterranean surface conditions and vertical instabilities (CAPE) advected over the Mediterranean basin.

In the simulation of these different convective cases, we want to explore the ensemble technique by taking advantage of the possibilities offered by a model such as the global System of Atmospheric Modelling, gSAM (Khairoutdinov et al., 2022), which can be used as both a global and a regional model. With gSAM it is possible to use not only different initial conditions, but also different resolutions and parameterizations.

The project aims to simulate different cases of extreme convection by primarily comparing simulations done over the Mediterranean at different resolutions. These include a Mediterranean tropical-like cyclone, Medicane Ianos, in September 2020, an event of scattered convective cells in the Umbria region occurred in August 2021 and a flood event due to persistent convection in November 2012 that affected central Italy. We expect to find little difference in the simulation of convection below a certain resolution in the case of Medicane Ianos, while we anticipate that the simulation will improve at higher resolution in the other cases. Indeed, the latter cases involve the organization of deep convective cells and within this phenomenology, the pressure difference preserved by the model gSAM can be relevant when comparing it with IFS.

Indeed, we will compare the IFS operational analysis and the observations with simulations carried out with gSAM. Given the data assimilation done at 9, km, we also expect gSAM simulations to have a different dynamic error propagation scale that may be crucial for capturing the phase of the moisture perturbation that induces deep convection.

The different energy conservation and formulation of the gSAM model compared to the IFS, can result in a difference in the vertical energy fluxes, and thus the conversion of the different meteoric species given by the different parameterizations used in gSAM. To analyze this point further, different microphysics schemes will be tested, the ones available for gSAM, to look at relevant effects on the convection dynamics due to evaporative and deposition processes in downdrafts and updrafts. This study also stems from the vast literature present on the existence of internal feedback in mesoscale convective simulations that can organize convection in the absence of boundary conditions or heterogeneous forcing, termed self-aggregation (Bretherton et al., 2005; Tompkins, 2001; Wing & Emanuel, 2014; Wing et al., 2020). Indeed, the observed convective organization, including squall lines, mesoscale convective systems and cyclones present signals of self-aggregation (Muller and Romps, 2018, Holloway et al., 2017). This is one of the aspects that will be studied by exploring the different internal feedback between moisture, convection and radiation in the events under consideration.

In general, we aim at finding an ensemble that can capture the dynamics of these different extreme convective phenomena. Thus, the main questions we want to address with this work are:

1. Can ensembles at finer horizontal resolution (from 9 km to 1 km) improve forecast of different types of extreme convective events?
2. Which type of convective extreme events are more susceptible to the increase of horizontal resolution? And why?
3. What are the key processes involved in the organization of convection in a warmer Mediterranean basin? How can we better simulate them through the ensemble technique?
4. Is there any advantage of implementing a regional high resolution ensemble system for capturing such events?

Methodology

1. gSAM model

The special project involves the extensive use of the gSAM (global System of Atmospheric Modeling), which is the extension of a cloud-resolving model, the System for Atmospheric Modeling

(SAM), to global domains (Khairoutdinov et al., 2022). gSAM is formulated on a latitude-longitude grid and uses an anelastic dynamical core with a single reference profile in temperature, humidity and pressure. Its governing equations differ somewhat from other anelastic models. For quasi-hydrostatic flows, they are isomorphic to the primitive equations in pressure coordinates, used by many GCMs like the IFS, but with the globally uniform reference pressure playing the role of actual pressure. Regarding the conservation of moist processes, gSAM follows the formulation by Pauluis (2008), who replaced the conservation of potential temperature by conservation of frozen moist static energy $h_f = c_pT + gz + L_cq_v - L_f\, q_{\mathrm{ice}}$ (the sum of moist enthalpy and geopotential energy), where c_p is the specific heat of air, L_c, L_s, and $L_f = L_s - L_c$ are the latent heats of vapourization, sublimation, and freezing, q_v is water vapor mixing ratio, and q_{ice} is the frozen water mixing ratio. The prognostic equation for h_L is improved in gSAM with respect to SAM with the inclusion of the buoyancy term which is itself expressed using absolute temperature. It is important to include the effect of the buoyancy flux for conservation of total energy as it opposes the generation/sink of the vertical kinetic energy by the buoyancy.

Many Physics packages are available in gSAM, directly inherited by the SAM mode. Here we report only the ones regarding the microphysics, which will be the subject to a direct evaluation. These are: the original SAM's single-moment microphysics and three comprehensive bulk microphysics modules, the Morrison et al. (2005), Thompson et al. (2008), and P3 (Morrison & Milbrandt, 2015). The land surface module is based on the Simplified Land Model (SLM). There are 16 land types defined by visible and near-infrared albedos, leaf area index, characteristics of the root system, and roughness length. The output of SLM includes land and ice surface sensible and latent heat fluxes, surface albedo for visible and near-infrared radiation, surface skin temperature for longwave radiation, and snow depth.

2. gSAM initialization

In gSAM, the existence of 3D runs makes it possible to run regional simulations of the atmosphere, for both Cartesian and Lat-Lon grids. The 3D forced regional runs can be used for simulations covering substantial areas—spanning the whole Mediterranean basin and Europe in general. 3D fields, from ERA5 reanalysis or the operational analysis at ECMWF on pressure coordinates (since gSAM operates on pressure coordinates), are employed to guide the simulation within the buffer zones. This method employs wall-like boundary conditions.

However, unlike traditional solid wall conditions where the normal velocity component is set to zero, the flow is nudged to align with observed flows, and horizontal pressure gradients are set to zero at the boundaries. The model continuously reads the 3D 'observed' fields from pre-prepared files in order to nudge the prognostic fields at the boundaries. Also, the velocity fields specifically can be weakly nudged to the observations everywhere in the domain. In our case we chose to do it over long time scales (12/24 hours). gSAM, after being give the initial 3D condition, will interpolate the data to its grid. The timescale for nudging is important. If this timescale is too short, the simulation could become overly constrained, essentially replicating the target dataset without any meaningful internal dynamics. Generally, for global simulations, the nudging timescale is recommended to be longer than 6 hours to maintain a balance between model freedom and adherence to observed. Hence the choice of 12 to 24 hours. Furthermore, the model assumes that the run time falls within the period covered by the nudging data files. It then reads and linearly interpolates the data to align with the current time step of the run. For all the considered cases the initial conditions will be interpolated at different resolutions from the ECMWF operational analysis at 9 km.

3. **gSAM resolution**

GSAM can interpolate the initial condition to a uniform grid in latitude and longitude. The chosen grid resolutions to run the simulations, as reported in Figure 2, are 9 km, 4 km, 2 km and 1 km. The starting point id 9 km to adhere to the operational analysis initial conditions resolution, then, the resolution is halved with each new run, until reaching the 1 km resolution, which is the limit for considering using gSAM as a cloud resolving model.

4. **gSAM microphysics**

As mentioned above, the evaluation of the capabilities of the gSAM model in capturing convective extreme events, will be evaluated also by considering changing the microphysics. The three comprehensive bulk microphysics modules enslisted above, the Morrison et al. (2005), the Thompson et al. (2008), and the P3 (Morrison & Milbrandt, 2015) schemes, will be used for each simulation.

5. **gSAM ensembles**

Lastly, to assess the validity of the results, to explore the convection variability of the simulations and to test the use of ensemble forecasting with the gSAM model in the Mediterranean area, we plan to run each of the simulation mentioned above as 8 members ensemble. In gSAM this can be carried out in the 3D forced regional runs with a specific setting that produces an ensemble by seeding the random-number generator differently for each ensemble member, creating initial noise variations.

6. Simulation Setup and Domain

For each case study, all simulation will be carried out on a single domain over the Mediterranean basin (see Figure 1 below) with a horizontal resolution of 9 km, 4 km, 2km, and 1 km.

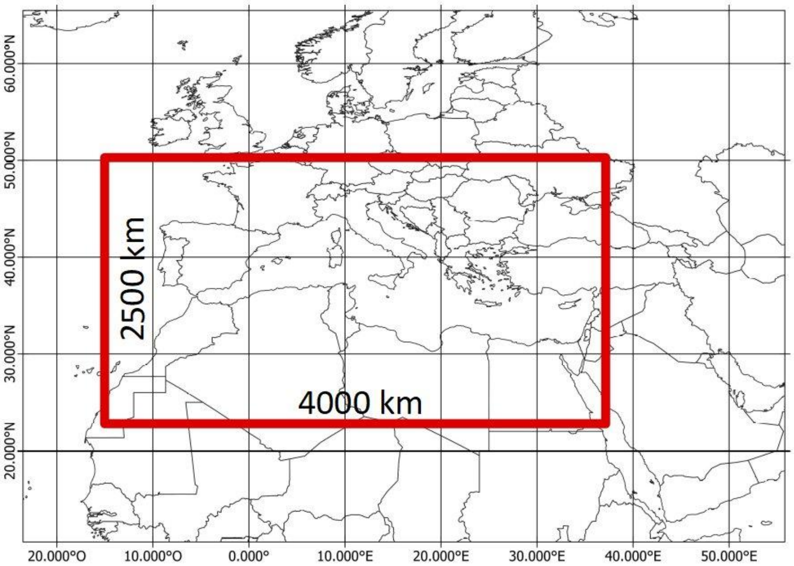

Figure 1: Simulations fixed regional domain over Europe, comprising the Mediterranean region under study.

Then, for each simulation, an 8-member ensemble, besides the control run will be produced. Another sensitivity will be tested, by changing the microphysical scheme (as shown in Figure 2). This is specifically done to look for the impact of microphysical processes in the dynamics of convection (change in updraft and downdrafts) affecting its convergence and divergence.

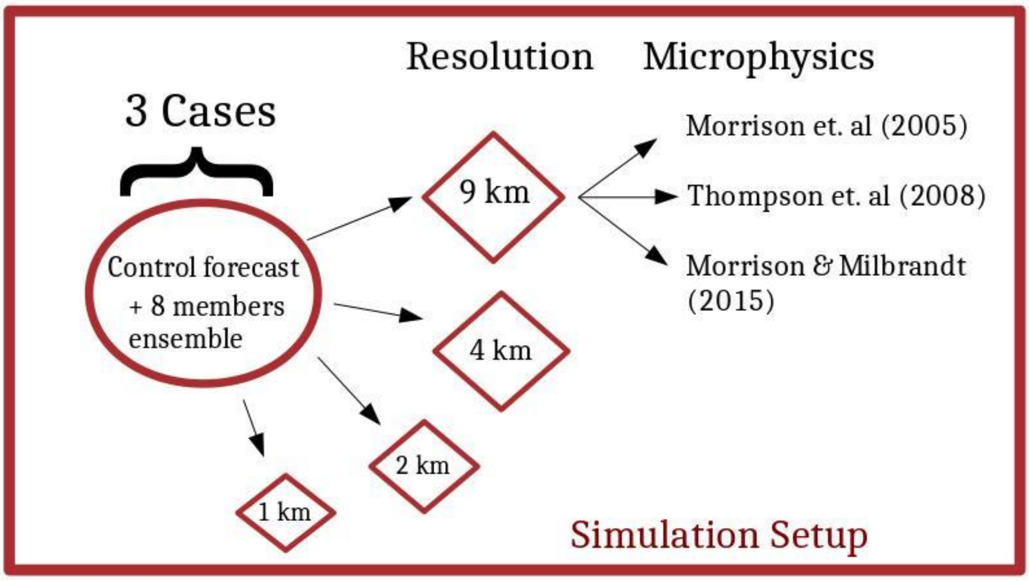

Figure 2: Simulations setup Summary. The same setup is valid for each case study chosen.

The chosen cases

1. **Mediterranean Tropical like cyclone, "Medicane" Ianos, of September 2020:**

Medicane Ianos impacted eastern Mediterranean between the 15th and the 20th of September 2020, hitting Greece specifically with strong winds, precipitation and storm surges. It developed over high sea surface temperatures, presented intense convection and between the 17th and the 18th exhibited a deep warm core, similarly to a tropical cyclone (Lagouvardos, et al., 2022). Predicting Ianos presented a challenge for operational forecast due to the representation of deep convection and its interaction with the large-scale flow in which it was embedded (Saraceni et al., 2023).

2. **Convective extreme event over Umbria Region of August 2021**

   On August 23, 2021, an exceptional and sudden thunderstorm event occurred and affected Umbria Region. Extensive damage was recorded and highly dangerous situations for human safety occurred (falling trees, damage to building roofs, etc.). It was attributed to the interaction between cool Atlantic air from northern Europe and a milder circulation of African origin flowing along the central and western Mediterranean. The stationarity of the line of convergence allowed for a continued source of energy and moisture to the storm system. The thunderstorm system was found to be composed of a series of precipitation nuclei aligned in a west-east direction. Satellite images showed a typical structure of a "Convective System at Mesoscale" (MCS) defined as a "V-Shape" indicative of the extreme intensity of the updrafts that were created within the various storm cells (Event Report for the Umbria Region, 2012).

3. **Flood event over Umbria region of October 2012**

   Between November 11 and 14, 2012, Umbria was hit (as well as Tuscany and Lazio northern Lazio) by a flooding event that resulted in extensive damage. The rainfall recorded was intense and persistent over all of Umbria brought about by continuous thunderstorm lines from the Tyrrhenian Sea. On November 11th the presence of an extended and deep cut-off from the Norwegian Sea all the way over the Middle Atlas Morocco met with the ascending branch of the polar jet stream over the Western Mediterranean. This resulted, in the following hours, in the development of a "Warm Conveying Flow" over southern Italy and the Adriatic, immediately followed on its western edge by a cold front. This configuration was the real driving force behind the convective activity. Advection of warm and humid air from the sea was an important factor in the convection maintenance. Local-scale forecasting weather models and the official Weather Bulletins over the area predicted, the days preceding and close to the event, a lower persistence of the phenomenon than that which then actually occurred on the regional territory, providing, therefore, an underestimation of the expected total rainfall (Event Report for the Umbria Region, 2021).

Validation and Analysis

For the validation of the simulations, the ECMWF 9km operational analysis will be used as the primary data source. Additionally, available observations will be utilized. Specifically, global datasets of precipitation observations from satellites (GPM-IMERG or GPCC) as well as observations from the

Mediterranean basin, including buoys and wind observations, both in Italy and in the Mediterranean in general, will be employed. Regarding the extreme convection events that occurred over Central Italy, a network of ground-based stations is available (Silvestri et al., 2022), which allows us to directly verify the precipitation simulation with ground-based precipitation in those cases. In the study of convection, various types of energy conservation budgets will be used to characterize physical processes and convective feedback.

Justification of the Computer Resources

In order to estimate the computing resources needed for the project, we ran a test of the SAM model at horizontal resolution of 1 km over a domain with a grid of 768 x 768 point (768 km x 768 km). For one day of simulation, we spent about 16.000 SBU and 35 GB of storage. Such numbers will be taken as reference for calculating the computer resources for our project. In particular such simulation cost can be compared to running a simulation with horizontal resolution of 4 km over the Mediterranean Basin, which we considered here to have an extension of about 4000 km x 2500 km, for a total of 1000 x 625 grid points. Then we considered an average length of simulation of about 5 days and a total number of ensembles of 27 (1 control run x 3 microphysics perturbations x 8 ensemble members). In the following we summarise the computational resources and the scientific plan as estimated from this preliminary test. We will also request for additional small amount of SBU and Storage to consider additional testing and/or possible errors.

Horizontal resolution Δx (Med Basin: 4000 km x 2500 km)	**Simulation days**	**Ensemble (3 micro+ 8 initial + 1 control)**	**Number of events**	**Total SBU and storage**
Δx = 1 km *Grid points = 4000 x 2500* *SBU/day= 64.000* *GB/day= 140*	*X 5 days*	*X 27 Ensemble*	*X 3 Events*	*SBU= 26.000.000* *TB= 60*
Δx = 2 km *Grid points = 4000 x 2500* *SBU/day= 32.000* *GB/day= 70*	*X 5 days*	*X 27 Ensemble*	*X 3 Events*	*SBU=13.000.000* *TB = 30 TB*
Δx = 4 km *Grid points = 1000 x 625* *SBU/day= 16.000* *GB/day= 35*	*X 5 days*	*X 27 Ensemble*	*X 3 Events*	*SBU = 6.500.000* *TB = 15 TB*
Δx = 9 km *Grid points = 4000 x 2500* *SBU/day= 8.000* *GB/day= 18*	*X 5 days*	*X 27 Ensemble*	*X 3 Events*	*SBU = 3.250.000* *TB = 8 TB*
Total				

SBU = 120.000 *GB = 265*	*600.000 SBU* *1325 GB*	*16.2 M SBU* *35 TB*	*50 M SBU* *105 TB*	***SBU = 60.000.000*** ***TB = 150*** ***(Including extra time and storage for testing)***

The amount of SBU and TB has been partitioned equivalently among the three years of the project.

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