REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE: Spain

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Project Title: Numerical modelling of Mediterranean weather extremes: new developments in the framework of the Triangle-based Regional Atmospheric Model (TRAM) and Model for Prediction Across Scales (MPAS)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SPESHOMA**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2022	
Would you accept support for 1 year only, if necessary?	YES **X**	NO ☐

Computer resources required for 2022-2024: (To make changes to an existing project please submit an amended version of the original form.)		**2022**	**2023**	**2024**
High Performance Computing Facility	(SBU)	50000000	50000000	50000000
Accumulated data storage (total archive volume)[2]	(GB)	20000	20000	20000

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.

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Extended abstract

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, disciplinary relevance, and justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests asking for 1,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.

Introduction

High-impact weather events (e.g., heavy precipitation, flash flooding, large hail, intense winds) produce substantial socioeconomic impacts worldwide, including human casualties and property loss and damage (CRED, 2016). In the particular case of the Mediterranean basin, estimated economic losses caused by floods were EUR 34 billion between 1980 and 2015 (EU Floods Directive 2007/60/EC, https://www.eea. europa.eu/data-and-maps/data/european-past-floods), while fatalities associated with these events exceed 2000 (e.g., Petrucci et al., 2018). The Mediterranean region is highly exposed to severe weather events owing to the presence of complex orography surrounding the area favours deep convective development by acting as a direct lifting mechanism and also modifying the mesoscale flow. Indeed, orographic anchoring often produces quasi-stationary convective systems over individual basins. This fact combines with the presence of steep small catchments with fast response times can generate devastating flash floods (Garambois et al., 2014). Furthermore, during late summer and especially autumn, when the maximum climatological frequency of flash flood producing heavy precipitation episodes (HPEs) takes place (Tudurí and Ramis, 1997; Llasat et al., 2010), the warm Mediterranean Sea acts as a heat and moisture source. The warm and moist air at low levels combined with the presence of cold mid-levels disturbances increases convective instability. Some recent remarkable examples of these episodes in Spain, which have been thoroughly analysed by the proponents of this special project, are the catastrophic flash floods in Sant Llorenç, Mallorca (October 2018; Lorenzo-Lacruz et al., 2019) and in south-eastern Spain (September 2019; Hermoso et al., 2021a). These episodes entailed thirteen and seven causalities, respectively and economic losses of hundreds of million EUR.

Socially relevant aspects of precipitation, such as timing, location, or intensity are difficult to forecast with enough accuracy. However, the extraordinarily fast development of flash floods demands to implement protective measures to be rapidly activated. Furthermore, given the typical small size of the catchments in the area slight mismatches in rainfall intensity or location can be highly consequential in terms of runoff. Thus, providing useful information for civil protection agencies to take effective actions is a major challenge. In this context, a probabilistic approach is required to account for the inherent uncertainties involved in numerical weather prediction (NWP), namely in initial and lateral boundary condition and in model formulation. The theoretical framework of this approach is based on the Liouville equation (Ehrendorfer, 1994; Hermoso et al., 2020a), but the unfeasibility to solve this equation for a realistic atmospheric system with millions of degrees of freedom compels to adopt the modest technique of ensemble forecasting. Under the ever-present limitation of computational resources an intelligent sampling of the probability density function (PDF) of the system must be performed in order to capture fast-growing error modes. In this sense, the tailored bred vectors, designed and tested by some of the researchers involved in the proposed project and based on generating perturbations across a wide range of scales, has shown potential to improve diversity and skill of mesoscale ensemble prediction systems (EPS; Hermoso et al., 2020b). Moreover, data assimilation (DA) methods and in particular Ensemble Kalman Filter (EnKF) can improve the representation of IC in meso- and convective-scale (e.g., Tanamachi et al., 2013; Marquis et al., 2016; Poterjoy et al. 2017). In the specific case of the Mediterranean region, which features scarcity of in-situ observations, DA can improve the forecasting of high-impact weather phenomena by advecting information from terrestrial areas and also by assimilating remote sensing observations, which, in contrast to in-situ observations, provide homogeneously distributed data over maritime areas.

Furthermore, model uncertainties, mainly related to the representation of subgrid processes by means of physical parameterizations, deserve special attention. The most extended methodologies to account for model error in EPSs are the use of multiple parameterization suites across different ensemble members (i.e., multiphysics) or stochastic parameterizations. In this latter case, popular approaches include stochastically perturbed physics tendencies (SPPT; Buizza et al., 1999) and stochastic kinetic energy backscatter (SKEB; Shutts, 2005). Additional methods focus uncertainty at the process level by stochastically perturbing relevant and uncertain specific parameters within physical parameterizations. Some prevalent techniques are the random parameters (Bowler et al., 2008; McCabe et al., 2016) and stochastically perturbed parameters (Jankov et al., 2017; Lang et al., 2021). In this vein, an application of the random parameter strategy to the microphysics parameterization, which is crucial for the simulation of deep moist convection has been carried out. The inclusion of microphysics perturbations resulted in an increased diversity and skill under certain conditions (Hermoso et al., 2021b).

Recent previous research of the proponent team has been based in the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), developed by the Mesoscale and Microscale Meteorology (MMM) Laboratory at the National Centers for Atmospheric Research (NCAR). The main objective of this special project is to adapt and expand several ensemble prediction strategies to other two atmospheric models: the Triangle-based Regional Atmospheric Model (TRAM) and the Model Prediction Across Scales (MPAS)-Atmosphere. The former is a prototype of a nonhydrostatic fully compressible model developed by the leading researcher of this project. A simplified version is introduced in Romero et al. (2019), and is formulated using a mesh of equilateral triangles. It is planned that the model is extend into a full-realistic 3D model for limited area domains. The latter is a model developed by NCAR/MMM. Although the WRF modelling system is mature, it is widely used by the atmospheric modelling community (Powers et al., 2017) and it will be supported and maintained in the near future, increasing developing efforts are devoted to MPAS. In this context, the applicant group will need to migrate from WRF to MPAS in order to maintain the impact of its research, which involves adapting the mentioned techniques to these new modelling systems.

Scientific plan

The general objective of this special project is to implement recently developed ensemble generation strategies targeted at the short-range meso- and convective-scale forecasting of severe weather in the Mediterranean region. In particular, special efforts will be devoted to improving the forecasts of flash floods. The specific objectives are the following:

1. Develop TRAM to an entirely 3D fully compressible numerical model.

2. Prepare MPAS to introduce already designed forecasting capabilities for WRF.

3. Testing of data assimilation initialisation strategies

4. Implementation of stochastic perturbations techniques into TRAM and MPAS

5. Analysis of catastrophic heavy precipitation episodes in the western Mediterranean. Application of data assimilation and stochastic techniques and multimodel intercomparison.

These aims are part of the goals established in the Spanish national project TRAMPAS, which is expected to begin on 1st September 2021.

The specific tasks proposed to accomplish the above objectives are detailed below:

Task 1: Development and evaluation of TRAM

Task 1.1: Inclusion of boundary conditions, physical parameterizations, and adaptation to real-case simulations

The simplified version of TRAM will be expanded to be used for realistic applications. In particular, the model will be adapted to ingest real meteorological fields to be used as initial and boundary conditions for meso- and convective-scale simulations. a damping zone near the domain edges, in the form of Newtonian and diffusion terms in the tendency equations, will be added in the model to relax the interior solution towards specified lateral BCs. Furthermore, all Coriolis and curvature terms will be included in the dynamical equations and map scale effects for a Lambert conformal projection (well suited for mid latitudes) will be incorporated. In addition, physics packages to account for different subgrid processes (e.g., microphysics, planetary boundary layer, land-surface, radiation) will be imported from WRF, requiring new predictive equations for mixing ratios of the different microphysics species. The appropriate operation of these modifications, as well as the optimum calling sequence of physical parameterisations will be assesses with a set of test runs.

Task 2.1: Evaluation of TRAM for idealised academic cases

The test cases to check the adequate performance of the model include simulation initialised with thermal bubbles, such as a rising thermal bubble in a calm and neutrally stable environment, interaction of large warm and small cold bubbles in the same environments, or development of a density current started with a cold bubble; simulation of mountain waves, flow around three dimensional mountains, mesoscale circulations (valley and breeze circulations) and simulation of mesoscale convective systems including squall-line and supercell simulations.

Task 2: Test MPAS capabilities for convective-scale forecasting

One of the distinctive features of MPAS (see https://mpas-dev.github.io/) is the use unstructured Voronoi meshes and C-grid discretization used as the basis for many of the model components. The unstructured Voronoi meshes, formally Spherical Centroidal Voronoi Tesselations, allow for both quasi-uniform discretization of the sphere and local refinement, avoiding the abrupt transitions of classical one-way or two-way grid nesting. The C-grid discretization, where the normal component of velocity on cell edges is prognosed, is especially well-suited for higher-resolution, mesoscale atmosphere and ocean simulations. Accordingly, the model incorporates a quite special solver of the NHFC equations (Skamarock et al. 2012) and contains some of the physical packages included in WRF.

Following the detailed documentation of the model, MPAS will be compiled on ECMWF systems and some test simulations will be performed in order to analyse model performance and scalability.

Task 3: Ensemble-based data assimilation

Task 3.1: Assimilation of Doppler radar observations

Reflectivity and Doppler radial wind velocities provide essential information of near-coastal dynamic and thermodynamic conditions. However, these observations are typically not quality controlled and present aliasing features together with very noisy data, especially at low levels (i.e., ground cluttering, attenuation of the radar signal, orographic false echoes, etc.). After post-processing and cleaning these data using different algorithms (e.g., Wradlib, BALTRAD or Py-ART), they will be assimilated by means of EnKF using EnKF within the Data Assimilation Research Testbed (DART) software (Anderson et al., 2009). DART provides the observation operators required to assimilate different types of observations, including reflectivity and radial velocities from radar. Data from AEMET, MeteoFrance and other radar meteorological services will be gathered for each case study.

Task 3.2: Assimilation of satellite radiances

Extreme weather events in the Mediterranean region regularly initiate offshore far from radar coverage. In these cases, satellite observations, especially radiances, are fundamental to obtain an adequate representation of the atmospheric state. However, no observational operation for radiances are currently available in DART, thus requiring an adaptation of such operation from an additional source. In this context, the Gridpoint Statistical Interpolation (GSI) system, which is a variational DA used in a variety of forecast models, including the Hurricane Weather Research and Forecasting model and NASA's Goddard Earth Observing System model, will be used to obtain radiance observational operators. We plan on testing the use of Advanced Microwave Sounding Unit-A and Unit-B, Microwave Humidity Sensor, IASI temperature and humidity profiles, and AMSU-A.

Task 4.3: Evaluation of the performance of various Kalman filters

EnKF is only one type of approach of ensemble DA algorithms based on Kalman filters. The performance of alternative of other schemes, such as the Local Ensemble Transform Kalman Filter (Hunt et al., 2007) or the Adjustment Kalman Filter (Anderson, 2001) over the Mediterranean area remains unknown. Thus, experiments testing these methods in the context of extreme weather forecasting will be conducted.

Task 4: Implementation of stochastic schemes

Task 4.1: Introduction of additional physical parameterizations into TRAM and MPAS

Physical parameterizations appropriate for high-resolution simulation will be implemented into TRAM and MPAS models. More specifically, the National Severe Storms Laboratory microphysics scheme (Mansell et al. 2010) and the Mellor-Yamada and Nakanishi Niino (Nakanishi and Niino 2006) boundary layer parameterization will be introduced to both models. The latter is already available in MPAS.

Some test simulations will be performed in order to verify the proper operation and consistence of the added parameterizations.

Task 4.2: Application of stochastic schemes to physical parameterizations and model dynamics

Various popular stochastic techniques will be implemented in TRAM and MPAS and tested. Popular strategies such as SPPT or SPP will be introduced, together with a version of random parameters for microphysics already tested for WRF (Hermoso et al., 2021b).

Furthermore, TRAM is an ideal candidate to test the inclusion of additional stochastic parameterizations to other terms of the state variable tendencies, considering the in-depth knowledge of the model of some of the proponent team members.

Task 5: Application to Mediterranean high-impact weather

Task 5.1: Ensemble experiments based on initial condition perturbations

Ensemble generation strategies based on initial condition perturbations, extensively used by the proponent group, such as downscaling or breeding will be tested using TRAM and MPAS. These techniques will be applied to catastrophic episodes, for instance the Sant Llorenç (Mallorca) case of October 2018 or the València/Murcia case of September 2019. In this sense, a selection of heavy precipitation episodes over the western Mediterranean is in progress within the current special project in order to evaluate these ensemble generation strategies in WRF. Therefore, a set of extreme episodes, together with a benchmark WRF performance will be available.

MPAS capability of refining horizontal resolution over specific locations seems promising for convective-scale forecasting, as computational costs of running a simulation in a large domain can be substantially reduced by focusing over areas with more intense convective development.

Task 5.2: Stochastic ensemble experiments

Methods developed and implemented in Task 4.2 will be evaluated for the same episodes used in Task 5.1 in terms of diversity and skill. It is also planned to couple atmospheric outputs with a calibrated hydrological model in order to investigate the potential of each technique to predict flash flood events. However, verification tasks and hydrologic simulations are intended to be carried out outside ECMWF HPC facility.

Task 5.3: Combination of initial condition and stochastic parameterizations. Multimodel ensembles

Additional ensembles combining both error sources will be designed and tested against the ensembles produced in Tasks 5.1 and 5.2. In addition, the availability of different models allows us to design multimodel ensembles to consider supplementary sources of model uncertainty besides the representation of subgrid processes.

Tasks 1 and 2 are planned to be developed during the first year of the special project, along with part of the experiments of Task 5. The implementation of DA strategies and stochastic parameterisations is scheduled for the second and third year.

Justification of computational resources

The proposed activities rely on running multiple convective-scale simulations with horizontal grid spacing ≤ 2.5 km and 50 vertical levels, resulting in a highly computationally demanding setup. Since these experiments are aimed at investigating the potential of the proposed ensemble generation strategies to forecast extreme events, ensemble size must be moderately large in order to make a sufficiently vast sampling of the phase space to capture risk scenarios. Furthermore, the DART filter used for data assimilation is an extremely demanding algorithm that needs the entire statistical description of the atmosphere (i.e., all ensemble members) in memory to perform the ensemble assimilation step. Therefore, this process requires massive use of memory, disk access and CPU.

This proposed experiment configuration has not been tested for TRAM or MPAS, but the cost of running a similar setup for WRF is approximately 1 million SBU for each ensemble experiment and a similar cost for the assimilation step on the current Cray system. Assuming that the cost in SBUs will be similar on the new Atos system, we estimate that similar computational resources will be required to run the proposed experiments for the other models. Indeed, previous scalability experiments performed with MPAS have shown efficient performance of this model under different architectures (Heinzeller et al., 2016). The requested 50 million SBUs per year provide enough flexibility to adapt the proposed experiments to the obtained results

The completion of the above ambitious scientific plan will provide the atmospheric modelling community with a new tool, suitable for a wide range of applications. In addition, the focus on extreme events will provide improvements in the understanding and modelling of these phenomena, which constitute a persistent threat to society. The extremely demanding setting needed to successfully accomplish these tasks requires access to world-class high performance computing facilities, such as the ECMWF infrastructure.

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