REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: Spain

Principal Investigator[1]: Luis Durán Montejano

Affiliation: Complutense University of Madrid (UCM)

Address: Department of Earth Physics and Astrophysics.
Faculty of Physics. Complutense University of Madrid.
Plaza de las Ciencias, 1. 28040 – Madrid (Spain)

Other researchers: Diego García-Maroto (UCM), Elsa Mohino Harris (UCM), Alejandro Martínez-Foronda (UCM), Iván Alfaro Rodríguez (UCM-CSIC)

……………………………………………………………….…………
…………………………………..……

Project Title: Hectometer-scale atmospheric and snowpack simulations for forecasting and climate change assessment

………………………………………………………………………….
…………………………………..……

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** …………..	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	2,000,000	2,000,000	900,000
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	30,000	40,000	50,000

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

EWC resources required for project year:		**2027**	**2028**	**2029**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

Principal Investigator: Luis Durán Montejano

Project Title: Hectometer-scale atmospheric and snowpack simulations for forecasting and climate change assessment

Extended abstract

All EMI R&D Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the EMI R&D Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous EMI R&D Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

Scientific context

Mountains play a fundamental role from a climatic and environmental perspective, as well as from an energetic and economic point of view, and they are the main source and reservoir of fresh water in many regions of the world (Barry R.G. 2013; Viviroli et al., 2020). In recent years, mountains are gaining greater prominence due to the growing concern about the impact of climate change on snow cover and precipitation (Hock et al., 2019; IPCC, 2022). Mountain regions have experienced significant warming since the beginning of the 20th century, leading to an average reduction in the snowpack (Marty et al., 2017). The increase in the fraction of precipitation falling as rain versus snow appears to be causing a decrease in both streamflow and groundwater storage in regions where snowmelt is the main source of recharge (Earman and Dettinger, 2011; Berghuijs et al., 2014).

Challenges in Mediterranean mountain systems are exacerbated by their inherent climatological and hydrological sensitivity to rising temperatures. These regions exhibit strong interannual variability in precipitation, a high proportion of rainfall relative to snowfall even during winter (Gonzaléz-Flórez et al., 2022; Lopéz-Moreno et al., 2024), and a critical dependence on the seasonal persistence of the snowpack to ensure summer water availability. Despite the progress made in recent years in what is commonly referred to as hyper-resolution simulation, two aspects of snowpack behavior remain particularly difficult to represent and predict: (1) the mechanisms of preferential deposition and transport of newly fallen snow induced by wind (Vionnet et al., 2017), and (2) the processes that determine snow sublimation, which account for significant losses in its water content. The former involves the spatial redistribution of fallen snow, in which fluid dynamics and uplift and deposition processes play a critical role. The latter is especially relevant in Mediterranean mountains, where water-resource losses through sublimation can reach or even exceed 30%, depending on atmospheric conditions and snowpack structure (Herrero et al., 2016; Sexstone et al., 2018; Hanich et al., 2024).

In recent years, high-resolution snowpack modelling techniques have advanced substantially (Gutmann et al, 2017; Reynolds et al., 2023; Essery et al., 2025). Some processes, such as precipitation and the diagnosis of atmospheric conditions, can now be simulated relatively realistically, allowing snow models to be forced consistently. Furthermore, there are areas with substantial instrumental deployments that have made it possible to successfully validate atmospheric simulation (Durán et al., 2017; Polo et al., 2019) .

Recently, state-of-the-art regional reanalysis products such as CERRA (Ridal et al. , 2024) and CERRA-Land (Verrelle et al., 2022) have offered richer historical information even at resolutions of a few kilometers over Europe, including the Iberian Peninsula and other important Mediterranean mountain systems. Global kilometer-scale climate simulations efforts such as nextGEMS (Segura et al., 2025) and DestinE (Doblas-Reyes et al., 2025) have also been a breakthrough in the modelling community allowing for regional studies about the snowpack in Mediterranean mountains (García-Maroto et al., 2025). These reanalysis and simulations also offer new forcing possibilities in order to drive hectometer-scale snow-atmosphere simulations (Reynolds et al., 2023, 2024). In this line, hectometer-kilometer and even decameter-scale resolution atmospheric and snowpack simulations of Iberian mountains have already been produced by the TROPA-UCM group within the context of project FIRN (PID2022-140690OA-I00) and the PhD thesis of Álvaro González-Cervera.

Research conducted using the available data has already detected trends and changes in the seasonal cycle of atmospheric and snow variables in Iberian mountains. These changes are expected to be more pronounced in mid-elevation mountains, where temperature variations lie very close to the 0-degree isotherm threshold. All Iberian mountain ranges are projected to experience reductions in the duration of the snow-covered season, while low to mid elevations could experience losses of more than 50% (García-Maroto et al., 2025). Under these conditions, even greater sublimation losses are anticipated, an aspect that may currently be inadequately represented in available models. Biases have also been detected in these global climate models (García-Maroto et al., 2025) that require further investigation and improvement and could benefit from more advanced snow modules.

This team has developed a model chain which uses outputs from the global ERA5 reanalysis, nesting the ICAR model (Gutmann et al., 2016). Its outputs are used to drive the FSM2 snow model (Essery, 2015), a multi-physics model that simulates snow accumulation and melt, allowing the calculation of variables such as albedo, thermal conductivity, snow density, turbulent exchange coefficient, and water retention and refreezing (snowpack hydraulics) as prognostic, diagnostic, or constant variables.

This modeling chain has produced excellent results, and is currently under review in the Journal of Hydrology (González-Cervera & Durán, 2021; 2022; 2023; 2024; 2026). **More than 20 years of sub-kilometer atmospheric and snow simulations have been already produced using very limited local computing resources and aggressive parallelization and optimization** (González-Cervera & Durán, 2026). These simulations, unprecedented in terms of spatial and temporal coverage for the study area of the Sierra de Guadarrama in Spain, have highlighted two major sources of uncertainty related to wind: the transport and redistribution of snow during and after snowfall, and the increase in sublimation.

In the future, the forcing data will be updated to use the high-resolution CERRA reanalysis (Ridal et al. , 2024). The modelling chain will be enhanced through the incorporation of the HICAR model (Reynolds et al., 2023) and the FSM2trans model (Mott et al., 2023; Quéno et al., 2023). This update of the simulation tools integrates several processes that are critical for achieving the project's objectives. In the case of HICAR (Reynolds et al., 2023), changes have been made to the advection scheme and wind solver in order to improve the representation of wind-flow in complex topographies, allowing for promisingly accurate simulations at resolutions of a few decameters while maintaining computational efficiency with benchmarking runs ~600 times faster than the WRF model. New physical parameterizations have also been included allowing for evaluation of hydrometeors and potentially improving the representation of preferential deposition. The FSM2trans model (Mott et al., 2023; Quéno et al., 2023) incorporates wind- and gravitational-induced snow transport, which is fundamental for this project's objectives and has already been shown to improve the representation of snow heterogeneity in 50m resolution simulations over a mountain basin in Davos, Switzerland (Berg et al., 2024) when compared to models without snow redistribution processes. A coupled version of HICAR and FSM2trans named HICARsnow (Reynolds et al., 2024) has also recently been developed. This coupled intermediate complexity snow-atmosphere model has already demonstrated its benefits, as allowing for continuous interaction between the atmospheric and snow components improves the representation of near-surface temperature and accounts for atmosphere-snow feedbacks in the snow sublimation processes that fundamentally change the quantification of these phenomena (Reynolds et al., 2024). More recently HICAR has also been coupled to the process-rich, multilayer snow model SNOWPACK (Reynolds et at., 2026) which will allow for an in-detail representation of the snowpack internal properties. Comparing both coupled models would help in understanding the advantages of a faster intermediate complexity model like FSM2 over a more complex model developed within a context of operational avalanche forecasting such as SNOWPACK.

Our team has a long history with monitoring mountain meteorology and manages multiple monitoring networks. We have detailed information on snowpack height, water equivalent, density and albedo which have already made possible a multivariable analysis of parameter sensitivity within the FSM2 model, showcasing a significant negative bias in snow density in the standard configuration (García-Maroto et al., in prep.). We have also developed new prototypes of inexpensive snow measuring devices that will allow the validation of this coupled model in Mediterranean mountains with a dense observational network allowing both for a better quantification of total water resource, snow density, wind transport and loss by sublimation in these areas potentially leading to improvements in the model chain. Team member Diego García-Maroto has a three-month (September to December 2026) stay planned at the WSL Institute for Snow and Avalanche Research SLF EPFL Laboratory of Cryospheric Sciences (CRYOS) as part of their FPU Fellowship (Spanish Ministry of Science and Universities, 2023), during which new simulations will be planned, computed and discussed with the model developers.

Objectives

The main objective of this project is ***to produce high-quality multidecadal hectometer-scale atmosphere and snowpack simulations using the HICAR-FSM2trans model chain***.

Secondary objectives include:

- Improving our understanding of the impacts of different model configurations by running multiple sensitivity experiments and validating results with our high-density snow and atmosphere meteorological measurement network.
- Developing a semi-operational snowpack forecasting model chain for Iberian mountains.

Scientific plan

The scientific development plan can be divided into the following approximate timeline:

- **Months 1-2**: Compilation of the models (HICAR, FSM2trans, SNOWPACK).
- **Months 3-6**: Running of test simulations and sensitivity tests in order to decide the best combination of physical parameterizations and model configurations for the study area, based on observed high-resolution data.
- **Months 6-18**: Production of high-quality multidecadal hectometer-scale simulations for at least one Iberian mountain region with the best model chain configuration as obtained from previous evaluation.
- **Months 12-24**: Analysis of the multidecadal production runs and possible production of new simulations at another mountain site.
- **Months 24-36**: Testing of the model chain as a semi-operational snowpack forecasting system for Iberian mountains.

Expected results

This project would allow us to produce multidecadal hectometer-scale (500 to 50 m) datasets of atmospheric (2m-temperature, wind speed and direction, rainfall, snowfall, radiation, etc.) and snowpack (snow depth, snow water-equivalent, snow density, snow temperature, etc.) variables. These datasets will be evaluated and publicly published as part of peer-reviewed scientific publications.

It will also allow us to increase the knowledge of the effects of different model configurations and physical parameterizations in the representation of complex climate phenomena in complex terrain. This knowledge will help to evaluate state-of-the-art models and thus to better target future needs for model development.

This fine-tuned model chain will also open new possibilities regarding operational hyper-resolution snowpack forecasts for Iberian mountains, which could be of great use for water management, risk assessment and winter tourism interests.

Justification of requested resources and other technical characteristics

The requested resources are aimed at allowing for the production of multiple nested hectometer-scale snow and atmosphere model runs. Even though the task may seem resource-intensive, our previous developments where more than 20 years of sub-kilometer atmospheric and snow simulations were produced using modest local computing resources and aggressive parallelization and optimization give us a great perspective into the possibilities that having access to an High Performance Computing (HPC) cluster will allow.

The models that will be used are conveniently documented in github and gitlab (HICAR, FSM2, SNOWPACK) and have been developed and intended for use on HPC machines. They make use of common libraries such as Parallel NetCDF4, FFTW and PETSc.