REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: .... Italy ....

Principal Investigator[1]**:** .... Andrea Alessandri ....

Affiliation: Institute of Atmospheric Sciences and Climate, National Research Council of Italy (ISAC-CNR)

Address: Via Gobetti 101, I-40129 Bologna, Italy

Other researchers: Annalisa Cherchi (ISAC-CNR), Emanuele Di Carlo (ISAC-CNR), Marco Possega (ISAC-CNR), Vincenzo Senigalliesi (UNIBO, ISAC-CNR), Simone Gelsinari (ISAC-CNR), Franco Catalano (ENEA)

Project Title: Improve representation of hydrological processes for the next generation of Earth system models

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.)	2025	
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]	18000000	12500000	4800000
Accumulated data storage (total archive volume)[2]	[GB]	54350	73000	84000

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.

Principal Investigator: ……… Andrea Alessandri ……………………….

Project Title: Improve representation of hydrological processes for the next generation of Earth system models

Extended abstract

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. 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 Special 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 Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 10,000,000 SBU should be more detailed (3-5 pages).

The Institute of Atmospheric Sciences and Climate at the National Research Council of Italy (ISAC-CNR) is member of EC-Earth (Consortium of research institutes from 10 European countries to collaborate on the development of a European Earth system model), where it coordinates the Land and Vegetation working group as well as the CMIP and Tuning working groups. ISAC-CNR is partner in several international efforts including European Union projects, WCRP activities in the context of the Coupled Model Intercomparison Project (CMIP) as well as new emerging initiatives in the framework of the Group on Earth Observations (GEO) aimed at exploiting latest land observations to improve and better constrain Earth system simulation and prediction.

ISAC-CNR is partner in the EU Horizon Europe project OptimESM ("Optimal High Resolution Earth System Models for Exploring Future Climate Change"). The main objective of OptimESM is to develop a new generation of ESMs for CMIP7 that benefits from ensuring a realistic representation of Earth system processes and their feedbacks, and in this framework ISAC-CNR aims to enhance the realistic representation of hydrological processes and their biophysical couplings with the atmosphere, which could potentially trigger abrupt changes in the climate system.

The Italian National agency for new technologies, Energy and sustainable economic development (ENEA) is member of the EC-Earth consortium, contributing in particular to the activities of Land & Vegetation and Climate Prediction working groups. ENEA is partner together with ISAC-CNR of the National Research Center for High Performance Computing, Big Data and Quantum Computing (ICSC), involved in the activities of the Spoke 4 – Earth & Climate. ENEA is taking part in the activities of CMIP and is partner in several EU Horizon Europe projects and other international and national efforts focusing on climate change and related impacts.

In this special project we will develop a more realistic representation of hydrology/groundwater in EC-Earth by including a global scale water table depth to replace free drainage bottom boundary conditions and achieve a more realistic representation of hydrological processes. To enable climate feedback driven by groundwater dynamics, we will attempt to include a simple groundwater model. This model could represent the recharge and discharge processes of water storage in an unconfined aquifer and include potential couplings with the effective root zone water storage capacity in the unsaturated soil. The effects of an improved representation of hydrological processes and the couplings with vegetation will be considered and assessed in a post-CMIP6 and CMIP7 configuration of EC-Earth, including historical and future scenario simulations.

Enhance representation of hydrology and vegetation processes for improved climate simulation and climate change projections

Water-limited regions facing increasing droughts related to climate change and intense human water use are extremely vulnerable to the transitions to drier eco-hydro-climatological regimes (Maestre et al., 2021; Alessandri et al., 2014; Garreaud et al., 2018; Pascale et al., 2020). In the longer term, the accumulating drought conditions may induce the decline of the groundwater levels which, combined with sea level rise, exacerbates the intrusion of salty water in coastal aquifers and surface waters (McFarlane et al., 2020). This may jeopardize the subsistence of groundwater-dependent ecosystems, increasing both the risk of progressive desertification, that could further feedback on the regional climate change, and the potential for geographical shifts in the transitional climate regions (Alessandri et al., 2014; Seager et al., 2019). In this respect, hydrological trends coupled with climate change are therefore potential tipping elements for dry shifts in transitional regions between wet and dry climates (Gleeson et al., 2020; Zipper et al., 2020).

However, the main important hydrological processes related to these transitions, such as water storage deficit/groundwater dynamics and vegetation water stress/root-depth dynamics, are crudely represented in state-of-the-art Earth System Models (ESMs). For instance, the land surface model included in EC-Earth (HTESSEL-LPJGuess; Alessandri et al., 2017; Döscher al., 2022) still lacks a representation of the groundwater and instead implements a free flux condition at the bottom of the unsaturated soil column. In this special project we aim at developing a more realistic representation of the subsurface hydrology by including a global scale representation of the water table depth to replace free drainage boundary conditions and more realistically account for the groundwater component. The water table depth will initially be estimated using global-scale data derived from land cover and pedological classifications, or from existing observational data combined with model products, such as those from Fan and Miguez-Macho (2013). To further allow the climate feedback operated by groundwater dynamics, we will subsequently attempt to implement a simple groundwater model by representing recharge and discharge processes of the water storage in an unconfined aquifer, which could be added as a single integration element below the soil of the land surface model. Investigation accounting for the dynamics of effective root zone water storage capacity will be considered as well.

Towards a CMIP7 version of EC-Earth

In this special project, we will use the latest version of EC-Earth (Döscher et al. 2022) which is being further developed in preparation of the CMIP7 coordinated experiments, that will include all the ESM developments thanks to the coordinated effort of all partners in the EC-Earth consortium and in previous and ongoing EU projects such as CONFESS, OptimESM, RESCUE, and TipESM. The developments leading to CMIP7 versions (v3.4.x and v4.x) of EC-Earth include improved process representation (improved treatment of aerosols and aerosol-cloud interactions, land vegetation, permafrost and hydrological processes) as well as the inclusion of novel components (such as dynamical ice sheets) that are relevant for the representation of climate feedbacks and the related risk of triggering fast and abrupt climate transitions. Furthermore, the components of the EC-Earth model are routinely upgraded to incorporate improved numerical schemes and revised encoding, enhancing high-performance computing (HPC) performances. The developments and improvements for the post-CMIP6 and towards CMIP7 version of EC-Earth will take place over time and evolve during this special project.

Summary of experiments and resources

Offline land-only simulations:

The hydrological developments in the HTESSEL-LPJGuess model will be evaluated in Offline Surface Model (OSM) simulations at the same horizontal resolution of the coupled simulations (T255) but forced by ERA5 meteorology and fluxes for the period 1979-onward. An interface to prescribe meteorological fields from observations/reanalysis is obtained from the latest OpenIFS release (https://www.ecmwf.int/en/research/projects/openifs). It is estimated that 2000 years of off-line simulations, including a sufficient spin-up period, will meet requirements to comprehensively assess all planned developments in HTESSEL-LPJGuess. These include parameterizing the water table depth and vegetation root zone water storage capacity. The OSM simulations with vegetation dynamics activated (LPJGuess) are planned to be accomplished during 2025.

A summary of the planned experiments and how they are distributed within the duration of the special project are summarized in Table 1.

Amip-type simulations:

Building on the analysis and improvements identified in land-only simulations, we plan to conduct a series of AMIP-type experiments (referred to hereafter as AMIP) to assess the impacts of these updates on land-atmosphere coupling. This will help us evaluate their effects on the representation of mean climate and its variability in water-limited regions, particularly in semi-arid and transitional climatic zones. This analysis is designed to be propaedeutic to the evaluation of climate change signals in the fully coupled ESM setup. This set of experiments will be performed with IFS+HTESSEL+LPJGuess with the updates already validated by the land-only simulations and forced with observed SST consistently with the CMIP7 protocol (if not available CMIP6 boundary forcing will be used; Durack and Taylor, 2017). We intend to perform about 245 years of AMIP-type experiments, corresponding to 5 members for the 1979-2021 reference period (i.e. 49 years including 6-years spin-up).
The AMIP simulations are planned to be accomplished during 2025.

A summary of the designed experiments and how they are distributed within the duration of the special project are summarized in Table 1.

Post-CMIP6 coupled historical simulations and projections:

A first set of post-CMIP6 sensitivity simulations will be performed to evaluate the effects of the improved representation of hydrological processes, taking as reference the control simulations already planned during 2025 in the framework of the OptimESM project. The post-CMIP6 experiments will be performed with the full ESM and consisting of an historical simulation covering the period 1850-2014 with CMIP6 forcing (here identified as HIST6), and two scenarios

(PROJ6) based on new sets of emissions following the latest climate policies, in phase with the release in the HE project OptimESM. One scenario, identified here as PA-REACH, reflects emissions that realize the Paris Agreement (i.e. that keep global warming below 1.5°C or 2°C relative to pre-industrial level), while the other, identified here as PA-FAIL, assumes delayed mitigation actions that overshoot the Paris target before returning to it at some later time. (UNFCCC, 2015; IPCC, 2018; 2021). The scenario simulations will span from 2015 to 2100, enabling evaluation of eco-hydro-climatological feedback resulting from realistic representation of hydrological processes. This includes assessing changes in the frequency and duration of meteorological, agricultural, and hydrological droughts.
The post-CMIP6 simulations are planned to be accomplished during 2025-2026.

A summary of the planned experiments and how they are distributed within the duration of the special project are summarized in Table 1.

CMIP7 coupled historical simulations and projections:

The core set of experiments with the full ESM configuration will consist of an historical simulation covering the period 1850-2021 with CMIP7 forcing (hereinafter HIST7), and two of the scenarios based on new sets of emissions following the latest climate policies being developed in the framework of CMIP7. The scenario simulations will cover at least the 2021-2100 time period. The extension to the end of 2200 will be optionally considered – also depending on the availability of additional resources – to better investigate and improve the understanding of processes and mechanisms at the base of recent climate change and in the projections for the coming centuries and investigate about the risk of triggering abrupt changes on a global scale.
The analysis of the core set of experiments performed with EC-Earth ESM will be focused on the identification of differences in the climate response over water limited regions across different scenarios. In this respect, we will investigate the attribution of changes in the occurrence of droughts to different global warming levels; furthermore, we will evaluate the risk of eco-hydro-climatological transitions and abrupt changes in water-limited domains. In this respect, a diverse set of drought indices will be evaluated and, depending on how sensitive they are to rates of change in the land cover and the impact of different feedbacks, they can be used to investigate the emergence of abrupt transitions in future projections according to the scenarios considered.

The CMIP7 simulations are planned to be accomplished during 2026-2027.

A summary of the planned experiments and how they are distributed within the duration of the special project are summarized in Table 1.

Configuration and justification of resources

For the OSM set of experiments we will use the offline version of HTESSEL-LPJGuess with an interface to prescribe meteorological fields from observations/reanalysis obtained from the latest OpenIFS release (https://www.ecmwf.int/en/research/projects/openifs). No parallelization of the code has been included so far in offline mode, therefore requiring 500 SBU per simulated year on Atos HPC2020. For the AMIP set we will use IFS+HTESSEL+LPJGuess at T255 resolution with 91 vertical levels in the atmosphere. Using 256 cores (2 nodes), the estimated required resources on Atos are about 18000 SBU per simulated year. For the core set of coupled simulations, we will use EC-Earth version3.4.x or version4.x (depending on availability) in its full ESM configuration

(with a closed carbon cycle) in the post-CMIP6 or CMIP7 version. The default resolution is T255 with 91 vertical levels in the atmosphere, and ORCA1 with 75 vertical levels in the ocean. Based on the current evaluation performed in the framework of the EC-Earth consortium, the optimal configuration on Atos HPC2020 is obtained considering the following components and related dedicated CPUs: IFS (560), NEMO (with PISCES activated; 280), XIOS (1), LPJG (32) by using 9 nodes (874 total cores). With this configuration, we estimate that the model requires on Atos about 40000 SBUs per simulated year. Overall, the total resources estimated for the project is rounded to **35,30 Million SBUs** (Table 1), which includes a buffer of 10% to account for failing jobs or additional short tests needed.
In terms of storage, the requirement is about 100 GB per year of coupled simulations, considering monthly means for the different model components and higher-frequency (i.e. 6-hours or 1-hour) atmospheric variables. Cmorization procedure via the ece2cmor3 tool will be used to reduce the raw output volume in case of exceeding storage output. For the offline simulations the requirements are of about 10GB per year for OSM and of about 30 GB per year for AMIP. Therefore, the total storage required for the project is **84 TB** (considering that 10 TB of OSM simulations are expected to be deleted after the first year).

A summary of the planned experiments, with details about the resources within the duration of the special project are summarized in Table 1.

Experiment name	Description	Resource per year (kSBU/yr)	Total years	Total resource (kSBU)	Storage (TB)	Scheduled year
Offline Land-only (OSM)	Offline Surface Model simulations for model developments.	0,500	2000	1000	20 (10 deleted after first year)	2025
Amip-type testing (AMIP)	Sensitivity testing of model developments	18	245	4410	7,350	2025
Post-CMIP6 Historical (HIST6)	Coupled historical simulations	40	132	5280	13,2	2025
			33	1320	3,3	2026
Post-CMIP6 Scenarios (PROJ6)	Coupled scenario simulations	40	138	5520	13,8	2025
			34	1360	3,4	2026
CMIP7 Historical (HIST7)	Coupled historical simulation	40	115	4600	11,5	2026
			57	2280	5,7	2027
CMIP7 Projections (PROJ7)	Coupled scenario simulations	40	105	4200	10,5	2026
			53	2120	5,3	2027

10% buffer			3210		
Total			**35300**		

Table 1: Experiments planned in this project, resource costs (kSBU), storage requirements (TB) and scheduled year of simulation. See text for details.

For comparison, the computing resources allocated (2nd column) and used (percent with respect to allocated; 3rd column) for the previous special project (SPITALES; https://www.ecmwf.int/en/research/special-projects/spitales-2022) in 2022 (that includes 16.150 Million additional resources granted) and 2023 are reported in Table 2.

Table 2. Use of SPITALES resources during the previous years of the project.

Year	Allocated budget	Percent used (with respect to request)
2022	24.150 Million	105%
2023	5. Million	86%

In case additional resources will become available through applications to PRACE and analogous programmes, further simulations will be performed with enlarged sampling (i.e. increase the number of ensemble members), increased projection length (extension to 2200).

References:

Alessandri A., M. De Felice , N. Zeng , A. Mariotti , Y. Pan , A. Cherchi , J-Y. Lee , B. Wang , K-J. Ha , P. Ruti, and V. Artale, 2014: Robust assessment of the expansion and retreat of Mediterranean climate in the 21st century. Nature Sci. Rep., 4, 7211, https://doi.org/10.1038/srep07211

Alessandri A, Catalano F, De Felice M et al. (2017) Multi-scale enhancement of climate prediction over land by increasing the model sensitivity to vegetation variability in EC-Earth. Clim Dyn 49: 1215–1237 https://doi.org/10.1007/s00382-016-3372-4

Döscher R, Acosta M, Alessandri A, Anthoni P, Arneth A, Arsouze T, Bergmann T, and co-authors, 2022: The EC-Earth3 Earth System Model for the Climate Model Intercomparison Project 6. Geosci. Model Dev. 15: 2973–3020 https://doi.org/10.5194/gmd-15-2973-2022

Durack P, Taylor KE (2017) PCMDI AMIP SST and sea-ice boundary conditions version 1.1.2 Earth System Grid Federation https://doi.org/10.22033/ESGF/input4MIPs.1161

Fan, Y., H. Li, G. Miguez-Macho (2013) Global patterns of groundwater table depth, Science, 339 (6122): 940-943, doi:10.1126/science.1229881

Garreaud RD, Alvarez-Garreton C, Barichivich J, Boisier JP, Christie D, Galleguillos M, LeQuesne C, McPhee J, Zambrano-Bigiarini M (2018) The 2010-2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. Hydrol Earth Sys Sci 21 6307-6327 https://doi.org/10.5194/hess-21-6307-2017

Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., et al (2020). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. Water Resources Research 56(4): e2019WR024957, https://doi.org/10.1029/2019WR024957

IPCC (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V. et al. (eds.)]

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V. et al. (eds.)]

Maestre, F.T., Benito, B.M., Berdugo, M., Concostrina-Zubiri, L., Delgado-Baquerizo, M., Eldridge, D.J., Guirado, E., Gross, N., Kéfi, S., Le Bagousse-Pinguet, Y., Ochoa-Hueso, R. and Soliveres, S. (2021), Biogeography of global drylands. New Phytol, 231: 540-558. https://doi.org/10.1111/nph.17395

McFarlane D, George R, Ruprecht J, Charles S and Hodgson G (2020) Runoff and groundwater responses to climate change in south west Australia. Journal of the Royal Society of Western Australia 103, 9–27. https://www.rswa.org.au/publications/journal/103/RSWA%20103%20p9-27%20McFarlane%20et%20al.pdf

Pascale S, Kapnick SB, Delworth TL, Cooke WF (2020) Increasing risk of another Cape Town "day-zero" drought in the 21st century. PNAS 117 29495-29503 https://doi.org/10.1073/pnas.2009144117

Seager R, Osborn TJ, Kushnir Y, Simpson IR, Nakamura J, Liu H (2019) Climate variability and change of Mediterranean-type climates. J Clim 32(10) 2887-2915 https://doi.org/10.1175/JCLI-D-18-0472.1

UNFCCC (2015) Adoption of the Paris Agreement https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Zipper, S. C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S. E., Gleeson, T., Porkka, M., et al. (2020). Integrating the water planetary boundary with water management from local to global scales. Earth's Future, 8, e2019EF001377. https://doi.org/10.1029/2019EF001377