REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Denmark

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Project Title: **EC-EARTH4: developing a next-generation European Earth System model based on ECMWF modelling systems**

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** NLTUNE	
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]	90,750,000	112,450,000	102,700,000
Accumulated data storage (total archive volume)[2]	[GB]	72,900	152,400	185,900

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]	0	0	0

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[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.

Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

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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).

EC-EARTH4: developing a European Earth System model based on ECMWF modelling systems

Introduction

The EC-Earth climate model is developed by the EC-Earth consortium that consists of nearly 40 European research institutes, meteorological institutes and universities from the ECMWF member states. The development of the EC-Earth model system has taken the "seamless prediction" approach to forge models for weather forecasting and climate change studies into a joint system. Thus the EC-Earth model system is designed to be based on models for short/medium-range to seasonal weather forecasts at the ECMWF so to enable the application of the advanced development in numerical methods and physical parameterizations at the ECMWF.

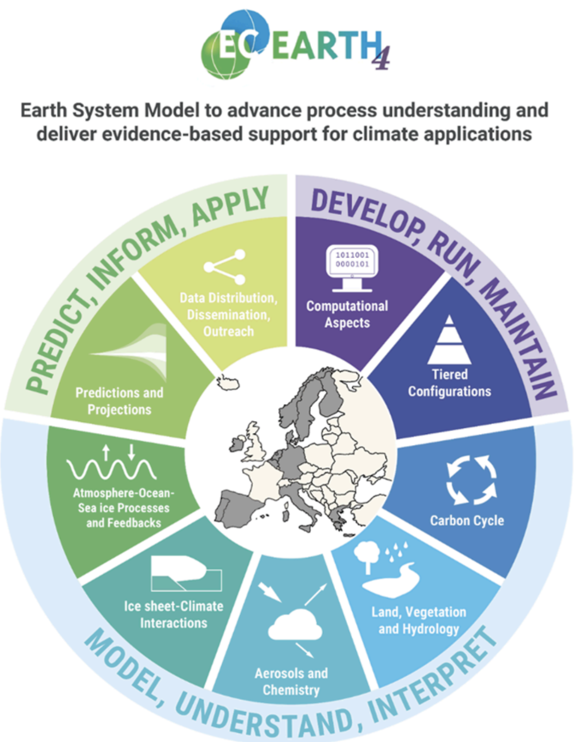

Figure 1: infographic for EC-Earth

In the past, the EC-Earth has been constructed with adapted versions of the atmosphere model IFS cy31r1 (for EC-Earth v2) (Hazeleger et al. 2012) and the cy36r4 (for EC-Earth v3), coupled with versions of the ocean model NEMO and the sea ice model LIM3 using the coupler OASIS. More precisely, the current generation of the model, EC-Earth3, consists of the IFS cy36r4, NEMO v3.6 and the OASIS3-MCT. In the past years, the EC-Earth3 has also further developed into an Earth system model by incorporated several Earth system components, e.g., the land vegetation model LPJ-GUESS, the atmospheric chemistry model TM5, and the ice sheet model PISM for Greenland ice sheet (Döscher et al., 2022, van Noije et al., 2021, Zhang et al., 2021, Wyser et al., 2020).

EC-Earth has been developed to a state-of-the-art model system successfully and contributed significantly to the Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6). In particular, EC-Earth3 in eight different configurations participated in the CMIP6 and 18 CMIP6 endorsed MIPs with ensembles of experiments, resulting in considerable scientific contribution to the IPCC 6th assessment report as well as numerous scientific publications, led by EC-Earth member and/or jointly with broad climate scientific community. These experiments have been used by several member states to provide climate services and national assessments for impact and adaptations. The model also provides a great tool for studies of the climate variability and predictability, feedbacks and response to forcings in the climate system. It has become one of the prominent models within the European "ecosystem" of Earth system models, as shown by the involvement in many European projects, including projects on high performance computing.

Since CMIP6, the consortium has been working on developing the new generation of the model, EC-Earth4. The ambition with EC-Earth4 is to have an Earth system model to advance process understanding and use it to deliver evidence-based support for climate applications. The new model is based on OpenIFS, and the new version of NEMO4. The first version of the EC-Earth4 comprises OpenIFS cy43r3, NEMO 4.2, OASIS3-MCT 5.0 and XIOS2.5. Preliminary testing and tuning of this version has been ongoing, thanks to the current special project SPNLTUNE which we are requesting to renew in this proposal. We are now upgrading OpenIFS to the newly available OpenIFS cy48r1, as we would stay close to the operational weather forecast model at ECMWF to take the advantage of the new development in the IFS.

The next goal of EC-Earth4 development is preparing a model suitable for participating in the CMIP7 FastTrack initiative (https://wcrp-cmip.org/cmip7/), with longer term objectives of participations in a number of CMIP7 community MIPs, as well as applications in other climate research and climate services. This initiative aims to rapidly assess the climate impacts of specific scenarios and policy choices, providing timely and crucial information for the upcoming cycle of IPCC reports. The ambitious timeline of the FastTrack initiative, with model experiments planned between mid-2025 and the end of 2026, is driven by the urgent need to understand the consequences of near-term climate change and the effectiveness of mitigation strategies. The resulting insights will inform international climate negotiations and help policymakers make evidence-based decisions to address the climate crisis. For each model configuration, approximately 1500 model years of run will be required for the core DECK experiments, with an additional 700 model years for ScenarioMIP runs.

EC-Earth4 roadmap and future developments

Continued development and investigation of the performance of EC-Earth at different resolutions and the schedule of advancements for individual components has led to a revised set of model configurations and resolutions which the consortium is planning to develop and use in the coming three years.

Updated table of core model configurations:

- **ECE4-GCM**: coupled (AOGCM) or AMIP (AGCM) mode, simple aerosols and mass fixer in OpenIFS 43r3v2 (to be upgraded to cy48r1 when ready with various adaptation to EC-Earth environment including coupling to other compliments and the inclusion of the aerosol module), Nemo 4.2, runoff mapper, interactive vegetation with LPJ-Guess 4.1, XIOS for OpenIFS/NEMO output and the coupler OASIS3-MCT 5.2
- **ECE4-ESM**: the full version of EC-Earth4 OpenIFS cy48r1 with simplified interactive aerosols (preferably M7 with prescribed oxidant fields) including proper mass fixer, ocean biogeochemistry (PISCES), XIOS. Other components, such as continental ice sheets, interactive chemistry (OIFS-AC) and a new River Routing model (CaMa-Flood) will be developed but included for FastTrack experiments based on their maturity. This model configuration should be able to run in either concentration-driven or emission-driven mode, so that esm-historical/scenario simulations are possible.
- **ECE4-LR**: a low resolution configuration similar to ECE4-GCM (no closed carbon cycle) for scientific purposes such as paleo-climate investigations.

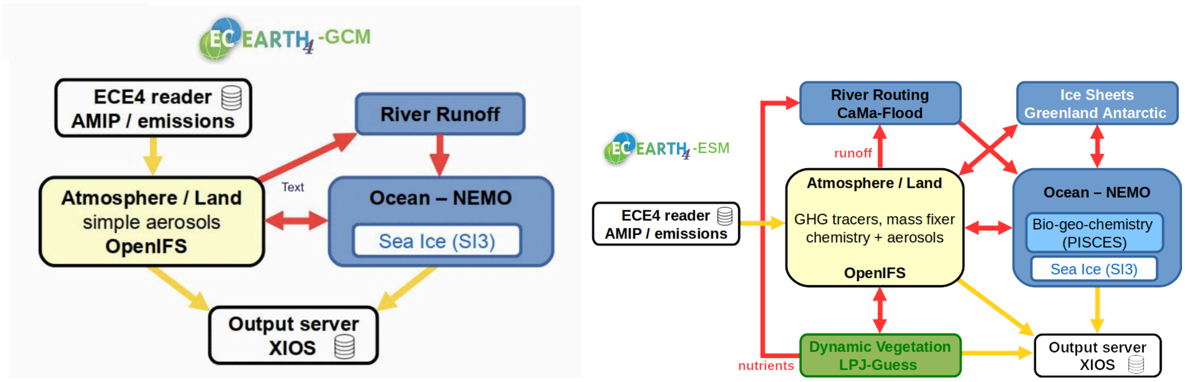

Figure 2: A schematic representation of the components and their coupling in the EC-Earth4-GCM configuration (left) and in EC-Earth4-ESM (right)

Model resolutions:

The main resolution for EC-Earth4 participating in the FastTrack experiments has been, for now, set to TL255L91/ORCA1 (in the following called standard resolution). Investigation of alternatives, ranging from atmospheric resolutions from Tco159 to Tco199 will be performed but issues such as significant Gibbs undulations in presence of sharp topography, compared to the computational cost are suggesting not to increase significantly the resolution of EC-Earth4 in comparison with EC-Earth3 and instead focus on an improved, well-tuned model at about the same resolution as the one used for CMIP6. For the same reason a low-resolution version of EC-Earth4 will be based on TL159/ORCA1 (as in CMIP6). A 2nd configuration with higher resolution, e.g. Tco319L91 and eORCA025L75 can be considered if there is interest in the community, possibly in GCM mode only and in any case will be developed and tuned independently for the FastTrack timeline.

Model tuning and validation

Tuning of EC-Earth4 aims primarily at minimising model biases in present-day simulations, with a realistic mean climate and variability, also as a basis for constraining uncertainty in future scenarios. Some elements of attention are the Sea Surface Temperature (SST) distribution (in particular addressing the biases in the Southern Ocean), realistic radiative fluxes and reduced biases both in global mean temperature and in its distribution. At equilibrium, in present-day or pre-industrial runs the model should reach a realistic range in top-of-the-atmosphere and surface radiative fluxes, without significant energy sources and sinks, while maintaining at the same time a realistic global equilibrium temperature. While model climate sensitivity is not an explicit target of tuning, but rather an emergent property of the model, it is crucial to identify processes affecting it and to test and validate them as far as possible. Tuning model parameter changes both to IFS and to NEMO should possibly be maintained at a minimum, keeping the model components close to the original as far as possible. The methodology employed for tuning is based on existing literature (Mauritsen et al. 2012, Hourdin et al. 2017). Simple global mean tuning targets will be expanded also to include regional biases, such as biases related to specific latitudinal bands or regions and other variables, such as those related to the water cycle and to an analysis of internal variability modes.

To these ends a range of tools have been developed and adapted to work with EC-Earth to facilitate model evaluation, such as the EC-Mean4 tool, a lightweight parallelized tool for evaluation of basic properties of Global Climate Models, such as global mean and climate model performance indices. This tool provides score cards (and corresponding numerical output) allowing to validate the model in terms of performance indices (such as those by Reichler and Kim, 2008) and biases, including regional biases. Another tool is represented by an extension of the ScriptEngine tool adopted by EC-Earth, allowing to perform real-time monitoring of model simulations with automatic publication of the results on the internal development server.

To achieve the tuning goals for coupled model configuration, each configuration will need a range of long model runs (about 500 years each) to produce reference model runs at equilibrium. Tuning changes applied to the coupled model will then require a range of further model integrations (about 100y each).

Workplan

The activities in the period 2025-2027, using computing resources from this Special Project, will primarily focus on 1) completing tuning of the EC-Earth-GCM configuration 2) tuning of the EC-Earth-ESM version for CMIP7 FastTrack and 3) performing the DECK (entry card) simulations for CMIP7 FastTrack with both configurations.

- 2025: Validation and testing of the target CMIP7 FastTrack AOGCM + preliminary ESM model configurations (following integration of new OpenIFS cycle - in particular cy48r1 - and additional components) + comparison with the AOGCM model version tuned in 2024. This will require at least 4x500 year coupled runs at standard resolution (for each configuration, present day and preindustrial). Further tuning activity will require a range of further coupled model integrations (we estimate the need for about further 2000y of runs). The final model configurations will also be tested at different, more expensive resolutions (e.g. Tco199) to verify if this may represent an alternative (done with shorter 20y integrations).

- 2026: The first half of the year will be dedicated to finalising tuning of the EC-Earth4-ESM configuration, also with the possibility of inclusion of components which have reached maturity only at that stage (such as inclusion of a new river routing scheme). This will require possibly another two equilibrium runs (they can be of only 250y since they can start from the previous version integrations). Both final model configurations will be used to perform the DECK integrations for CMIP7 FastTrack (currently estimated in 2x1600 years) and to perform at least one ensemble member run of 5 Scenario MIP scenarios (2 x 700 years) with each configuration (concentration-driven and emission-driven). First tests of the high-resolution version of the model (Tco319 or Tco399 + ORCA025) will be performed (only AOGCM, possibly two 30y runs).

- 2027: This year will be dedicated to developing the final CMIP7 version of the model (beyond FastTrack), implementing and tuning model components which were not included in the FastTrack ESM version and developing higher resolution model versions. Model retuning and long control simulations will be needed. In particular for the high-resolution simulations we estimate the need for at least 5 integrations of 30y each, plus about 1000y of equilibrium model runs in the standard-resolution ESM configuration and a total of 1000y of shorter tuning runs.
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In all years some resource will be dedicated to running a continuous testing, tuning and software validation framework in which each non-trivial pull request (merging into the main branch) will be associated with a set of standardised short AMIP and coupled experiments aiming at assuring the continued technical functionality of the code and monitoring of performance scores (comparison with observed climatology). We estimate an average of at least 500 model years to be needed each year to this end.

Justification of resources

Computing and storage resources

The following table summarizes revised estimates of core hours per simulated model year (CHPSY) of the current EC-Earth4 prototype, currently available, at some of the currently envisioned resolutions (a conversion factor o 17.06 between core hours and SBU has been assumed):

Configuration	**Core-hours / model year**	**SBU/year GCM**	**SBU/year ESM**	**Storage / model year**
TL159 AMIP	240 CHPSY	4,000 SBU/year	5,200 SBU/year	5 GB / y
TL159/eORCA1	400 CHPSY	7,000 SBU/year	9,100 SBU/year	10 GB / y
TL255 AMIP	500 CHPSY	8,500 SBU/year	11,000 SBU/year	15 GB / y
TL255/eORCA1	900 CHPSY	15,000 SBU/year	19,500 SBU/year	20 GB / y

Tco199 AMIP	2,500 CHPSY	47,000 SBU/year	61,100 SBU/year	29 GB / y
Tco199/eORCA1	3,000 CHPSY	56,500 SBU/year	73,500 SBU/year	34 GB /y
Tco319 AMIP	9,000 CHPSY	170,000 SBU/year	221,000 SBU/year	70 GB / y
Tco319/eORCA025	15,000 CHPSY	282,500 SBU/year	367,000 SBU/year	90 GB / y

Based on past experience with EC-Earth3 configurations, we estimate that the ESM version of the model requires, on average, 30% more than the AOGCM version.

Model storage requirements will depend on the specific data request by CMIP7 FastTrack (still to be developed). Based on EC-Earth3 experience we estimate the need for about 20 GB/y model year of storage for the output for standard resolution and we scaled the other numbers accordingly. Tuning output is reduced, so estimates are divided by 2 in the following.

According to the workplan illustrated above we estimate the following approximate needs

2025:

Model resolution	**Activity**	**Planned model years**	**Computing cost (SBU)**	**Storage cost**
TL255/eORCA1	coupled runs, ESM+GCM, PI + PD	1000 (GCM) 1000 (ESM)	15,000,000 19,500,000	40,000 GB
TL255/eORCA1	Tuning	500 (GCM) 1500 (ESM)	7,500,000 29,250,000	20,000 GB
TL159/eORCA1	Tuning/Validation	500	3,500,000	5,000 GB
Tco199/eORCA1	Short tests (6x20y)	120	7,350,000	2,900 GB
TL255/eORCA1	CI/CD	250 (GCM) 250 (ESM)	8,650,000	5,000 GB

Total in 2025: 90,750,000 SBU and 72,900 GB

2026:

Model resolution	**Activity**	**Planned model years**	**Computing cost (SBU)**	**Storage cost**
TL255/eORCA1	Updated tuning coupled integration	500	7,500,000	10,000 GB
TL255/eORCA1	DECK integrations for FastTrack	1600 (GCM) 1600 (ESM)	24,000,000 31,200,000	32,000 GB 32,000 GB
TL255/eORCA1	FastTrack Scenario MIP (5 scenarios)	700 (GCM) 700 (ESM)	10,500,000 13,650,000	28,000 GB
TL255/eORCA1	CI/CD	250 (GCM) 250 (ESM)	8,650,000	5,000 GB
Tco319/eORCA025	High-resolution tests (2x30y)	60 (GCM)	16,950,000	5,400 GB

Total in 2026: 112,450,000 SBU and additional 112,400 GB, cumulative storage 152,400 GB *

*) The tuning tests from the previous year do not need to be preserved.

2027:

Model resolution	Activity	Planned model years	Computing cost (SBU)	Storage cost
TL255/eORCA1	Final CMIP7 configuration long runs + tuning (ESM)	2000	39,000,000	20,000 GB
Tco319/eORCA025	High-resolution ESM model development and validation (5x30y runs)	150	55,050,000	13,500 GB
TL255/eORCA1	CI/CD	250 (GCM) 250 (ESM)	8,650,000	5,000 GB

Total in 2027: 102,700,000 SBU and additional 38,500 GB, cumulative storage 185,900 GB *
*) the tuning tests from the previous year need not to be preserved.

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