REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE: Denmark

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

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.)	2022	
Would you accept support for 1 year only, if necessary?	YES ☐	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)	100,000,000	115,000,000	140,000,000
Accumulated data storage (total archive volume)[2]	(GB)	90,000	150,000	225,000

[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.

Continue overleaf

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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, 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 3,000,000 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.

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

Introduction

Around 2006, the need for an Earth System Model (ESM) was recognized by various ECMWF Member States (MS). This effectively initiated the development of EC-Earth (see http://www.ec-earth.org). EC-Earth is both a model and a European consortium that develops and applies the model (38 European research institutions, meteorological institutes and universities are partners).

The earlier system EC-Earth2 (Hazeleger et al., 2012) approached the concept of "seamless prediction" to forge models for weather forecasting and climate change studies into a joint system. EC-Earth version 2.2 was based on an adapted version of the atmosphere model IFS 31r1, the Integrated Forecasting System of the European Centre for Medium-Range Weather Forecasts (ECMWF), as used in their seasonal prediction system 3. In addition, a configuration including the atmospheric composition model TM5 was developed (van Noije et al., 2014) and released as EC-Earth version 2.4. EC-Earth2 has been used for simulations under CMIP5 and in a range of climate studies (e.g. Koenigk et al. 2013, Seneviratne et al. 2013)

The current generation of the model, EC-Earth3, still leans on the original idea of a climate model system based on the seasonal prediction system of ECMWF. Development started in 2012 by re-designing the software infrastructure and updating the atmosphere model to IFS 36r4, corresponding to the ECMWF seasonal prediction system 4. More precisely, it is based on a newer cycle of ECMWF's IFS model (c36r4), the NEMO ocean model (v3.6), the LIM3 sea ice model, as well as H-TESSEL for the land surface. Coupling is provided by OASIS3-MCT. Various updates, improvements and forcings have been implemented and several components of the earth system (e.g., the land vegetation model LPJ-GUESS and the atmospheric chemistry model TM5) have been integrated into the model system. The model has been tuned for several intermediate versions and finally for the CMIP6 version, EC-Earth version 3.3 (Döscher et al., 2021).

EC-Earth has been developed to a state-of-the-art model system and as such contributed significantly to CMIP5, the model intercomparison project that fed into the 5th IPCC Assessment Report and to CMIP6 (participating in dozens of experiments scattered over 18 MIPs), providing a significant scientific contribution to the upcoming IPCC 6th Assessment Report. It also provided boundary condition data to downscale global climate change to regional levels in the framework of the CORDEX initiative. Scientific studies on the feedbacks in the climate system and on predictability of the climate system have been conducted with EC-Earth, which already led to dozens of scientific publications. Also, EC-Earth has become a prominent model within the European 'ecosystem' of Earth system models, as shown by the involvement in many European projects, including projects on high performance computing.

Adaptation of IFS for EC-Earth follows up on the strategy of mutual benefits between short/medium range weather prediction on the one hand and longer time scale climate prediction and projection on the other. While short term processes and feedbacks are expected to be covered well in the seasonal prediction system, longer term conservation and trends are the focus of climate model development. During the development process, EC-Earth has been able to feed back valuable information to ECMWF. Examples are a stochastic physics tendency conservation fix for humidity and energy (Leutbecher et al. 2017), forcing (tropospheric and stratospheric aerosol, ozone), including an implementation of tropospheric aerosol forcing as used in CMIP6 ("MACv2-SP") and an enhancement of the sensitivity to vegetation variability in HTESSEL/IFS (Alessandri et al., 2017).

The development of EC-Earth has now entered a new phase in its evolution, with a coordinated effort underway to develop a new version, EC-Earth 4, based on OpenIFS and NEMO 4. The adoption of OpenIFS as the atmospheric component in EC-Earth is the prerequisite for a tighter development integration between ECMWF and the Consortium, a faster development cycle and for expanding the user base of the model with a more permissive licensing scheme. A first, technically working prototype based on OpenIFS 43r3, NEMO 4.0.1, OASIS3-MCT 4.0 and XIOS 2.5 is already available. Intense development work is planned for the next three years, including continuous testing, validation and tuning of the model. In the following we describe the planned model configurations and how resources from this Special Project will be crucially employed for the development of EC-Earth 4.

EC-Earth4 roadmap and future developments

Planned EC-Earth4 developments

The development of EC-Earth4 includes several goals representing a significant advancement over EC-Earth3.

One activity is the development of an OpenIFS version with integrated interactive aerosols and atmospheric chemistry. This is a collaborative effort by several groups from the Consortium together with ECMWF. The aim is to develop an OpenIFS version with a CAMS based interface that is flexible enough to allow for different aerosol and chemistry schemes. The first configuration to be developed for EC-Earth4 will represent the aerosols using seven log-normal size distributions following the M7 scheme (Vignati et al., 2004). More precisely, the aerosol scheme will consist of the latest implementation of M7, with additional modules to describe the formation of secondary organic and inorganic aerosols, in interaction with tropospheric chemistry. Other processes such as natural and anthropogenic emissions, wet and dry deposition, sedimentation, and the calculation of aerosol optical properties will be described based on implementations in TM5, HAM and/or CAMS. The chemistry scheme will be based on the CAMS implementation (Flemming et al., 2015), with the Carbon Bond CB05 mechanism in the troposphere and optionally the BASCOE chemistry scheme in the stratosphere (Huijnen et al., 2016). The computational performance that can be achieved with such a configuration needs to be further investigated.

Another activity is the development of an Earth system model (ESM) configuration of EC-Earth4 with a fully integrated carbon cycle (ECE4-CC). This requires the coupling of OpenIFS to the PISCES biogeochemistry model from NEMO4 and the LPJ-GUESS land ecosystem and dynamic vegetation model. The transport of CO2 through the atmosphere will be described using a tracer in OpenIFS.

Other planned developments relate to a river routing scheme replacing the runoff mapper used in EC-Earth3 (replaced by CaMa-Flood), the use of the FLake model (already integrated in OpenIFS), H-TESSEL and LPJ-GUESS enhancements and an improved coupling between the two components, integration of the Greenland and Antarctic ice sheets through PISM and BISICLES, respectively, the introduction of the eORCA oceanic grid to simulate the ice-shelves dynamics and various more technical developments as the introduction of unified ECE4-reader able to preprocess several boundary conditions as SST/SIC and GHG emissions or the development of a mixed-precision version of EC-Earth.

Model configurations

Following the same strategy already adopted for EC-Earth3 in CMIP6, a range of different model configurations is also planned for EC-Earth4, designed to address a range of different scientific goals.

Specifically the following three main configurations are planned:

- **ECE4-GCM** (target date 2022): coupled (AOGCM) or AMIP (AGCM) mode, simple aerosols and mass fixer in OpenIFS 43r3v1 (to be upgraded to 47r3 when available), Nemo 4.0 (to be upgraded to 4.2), runoff mapper, with XIOS for OpenIFS/NEMO output
- **ECE4-CC** (Target date 2023) : minimal support for the Carbon Cycle with support for GHG tracers and various emissions (CMIP6, CAMS, etc.) in OpenIFS 43r3v2 or later cycle, LPJ-GUESS 4.1, NEMO/PISCES and a python-based ECE4 reader (for AMIP/emissions)
- **ECE4-ESM** (Target date 2024) the full version of EC-Earth4 OpenIFS 47r3 with atmospheric chemistry and aerosols, continental ice sheets, a proper River Routing model (CaMa-Flood) and XIOS output for major components (OpenIFS, NEMO, LPJ-GUESS). See figure 1 for a schematic representation of the planned configuration.
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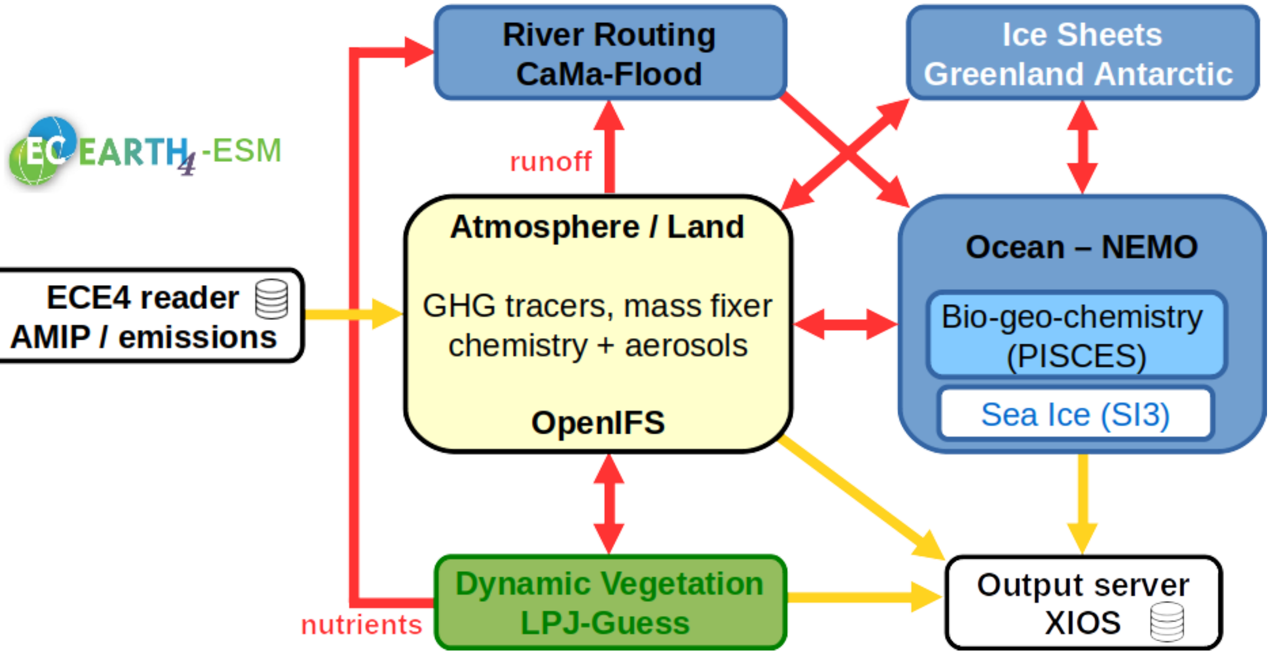

Figure 1: A schematic representation of the components and their coupling in the full EC-Earth4 ESM version ECE4-ESM

Multiple resolutions

User requirements cover a range of spatial scales, from low resolution for educational purposes, paleoclimate studies and long simulations, to regional analysis of extreme events and hydrological modeling, which needs high atmospheric and oceanic resolution. A limited number of resolutions will receive full support and will be tuned, and fully tested. In particular a low-resolution configuration of Tco95 for atmosphere (~100 km) with eORCA1 ocean (~1 deg) is planned to be used as the main development version, together with an intermediate resolution version (possibly Tco159/199, ~61/50 km) coupled with an eORCA1 ocean. A high resolution version (Tco319/Tco399, ~31/25 km), coupled with an eORCA025 ocean, will be developed once the intermediate resolution goals have been reached. A final decision on the intermediate and high resolutions will be made during the development process, but in the following we assume a choice for Tco199 and Tco319.

Model tuning and validation

The tuning activities of EC-Earth in the periods (2012-2014, 2016-2018, 2019-2020) have profited to a large extent from resources from the special project SPNLTUNE and have allowed to significantly improve EC-Earth 3, at standard (TL255) and at high resolution (TL511) and for preparing the EC-Earth3-AerChem CMIP6 configuration.

The tuning process of atmospheric parameters in EC-Earth4 will rely on the techniques developed for the tuning of EC-Earth3. In particular the atmospheric component of EC-Earth3 has been tuned with the goal of achieving a reasonably small radiative imbalance at the top of the atmosphere (TOA) at standard resolution (T255L91) in present-day atmosphere-standalone (AMIP) runs, using the CERES_EBAF_Ed4.0 dataset as a reference (Loeb et al. 2018). In particular the goal was to minimize the mean weighted absolute error in the global means of the net radiative flux at the surface, the TOA longwave flux, longwave cloud forcing and shortwave cloud forcing, with the first two fluxes considered most important. The net radiative flux at the surface included the latent heat contribution associated with snowfall which is not included in the latent heat flux stored by IFS. A series of convective and microphysical atmospheric tuning parameters was identified. Similar parameters have been commonly used also for the tuning of other climate models (e.g. Mauritsen et al. 2012). Changes in the tuning parameters have been adopted to avoid values too different to the values of the original IFS cycle. In order to proceed with tuning, the sensitivity of the model radiative fluxes to changes in these parameters was determined through a series of short AMIP runs for present-day conditions. The resulting linear sensitivities accelerate considerably the tuning process and reduce the number of simulations needed, allowing to construct a linear "tuning simulator" used to predict the impact of different combinations of tuning parameter changes on the target radiative fluxes and to determine combinations providing an optimal score. An iterative process was followed, alternating the construction of new sets of tuning parameters using the known sensitivities, AMIP tuning runs for present-day conditions (20 years, from 1990 to 2010) and the following construction of a new set of tuning parameters to correct the residual biases, allowing to converge rapidly to a desired radiative balance. During this process model biases in other fields were monitored using a Reichler and Kim (2008) metric. The tuning process also needs to assess the dependence of the (energy and mass) conservation properties and of the radiative balance on the timestep used and resolution (both horizontal and vertical). A significant dependence was found in EC-Earth3, making this an important point also for EC-Earth4.

As done for EC-Earth3, tuning the final coupled model will be aimed primarily at obtaining a realistic global climate at equilibrium in CMIP6 pre-industrial experiments, focusing in particular on the sea-ice distribution and extent, the near-surface air temperature distribution, atmospheric variability, the Sea Surface Temperature (SST) distribution (in particular the Southern Ocean temperature bias) and ocean transport due to the Atlantic Meridional Overturning Circulation (AMOC), while at the same time reaching a realistic average global temperature at equilibrium. The goal is to - where possible - modify only ocean and sea-ice parameters while maintaining the same atmospheric tuning (even if some changes may be needed). To this end we perform both a range of pre-industrial simulations and, for comparison, corresponding present-day simulations (using fixed 1990 forcing fields and compared to 2010 observations). Gregory plots (Gregory et al. 2004) are used to compare different coupled experiments, to anticipate their approximate equilibrium temperatures even when only partial results were available and to derive suggested corrections to the global net radiative forcing. Joint technical model development and model tuning, with resources provided by SPNLTUNE, have been crucial in order to allow the inclusion of EC-Earth in CMIP5 and CMIP6 and will be required for developing the next generation EC-Earth4. Several novel papers, including some very high impact papers, have been published including EC-Earth results (see also the bibliography at the end of this document).

Workplan

The activities in the period 2022-2024, using computing resources from this Special Project, will primarily focus on tuning the AO-GCM configuration. The work will be organized as follows:

- 2022-2023: Series of AMIP model runs (up to 20 years/run, 10 atmospheric parameters, at least 5 different parameter values, all model resolutions) aimed at determining model sensitivity to parameter changes to be used for tuning (Tco95 and Tco199 in 2022, Tco319 in 2023 - only 5 parameters and 3 parameter values explored for Tco319)

- 2022-2023 Validation and testing of the model following integration of new OpenIFS cycle (in particular cy47r3 in 2022) (at least one 500 year coupled run at Tco95 in 2022 and one 250 year coupled Tco199 run in 2023)

- 2022-2024: Specific AMIP and coupled model runs (up to 10 years/run for AMIP, 50 years/run for coupled) aimed at exploring specific development issues (such as testing new parameterizations, changes in coupling between the components). We estimate a need for at least 10 such AMIP experiments / year and 10 coupled runs / year, at Tco95 in all years. Starting from 2023 we estimate a need for performing tests with Tco199 (10 AMIP and 10 coupled runs/year).

- 2022-2024 Implementation of a continuous testing, tuning and software validation framework:
  In the new git development framework, each non-trivial pull request (merging into the main branch) will be associated with a set of standardized short AMIP and coupled experiments aiming at assuring the continued technical functionality of the code and monitoring of performance scores (comparison with observed climatology). Major merge requests will trigger a series of standardized experiments aimed at rapid tuning, with the goal of maintaining at all times a tuned version of the model in the main branch. This will require frequent retuning runs following each major model merge. We estimate a need for at least 5 retunings /year with 4 runs of 10 years AMIP each, at Tco95 each year and 5 AMIP retuning / year at Tco199 (starting in 2023). For Tco319 a single initial AMIP tuning will be performed in 2023 (up to 4 runs of 10 years each).

- 2024 Longer equilibrium experiments of the coupled model (up to 500 years, present day and historical) at intermediate resolution (Tco199 eORCA1L75). in order to assess model biases and to tune ocean parameters. One 100-year coupled run at Tco319 eORCA025L75 in 2024.

- 2023-2024 Long equilibrium experiments with the high resolution model and proper tuning of the high resolution model will be performed with external resources additional to those provided by this special project.

Justification of resources

Computing resources

The following table summarizes 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 of 18.82 between core hours and SBU has been assumed) :

Tco95 AMIP	500 CHPSY	9500 SBU/model year
Tco95/eORCA1	900 CHPSY	17000 SBU/model year
Tco199 AMIP	2500 CHPSY	47000 SBU/model year
Tco199/eORCA1	3000 CHPSY	56500 SBU/model year
Tco319 AMIP	9000 CHPSY	170000 SBU/model year
Tco319/eORCA025	15000 CHPSY	282500 SBU/model year

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

2022:

Model resolution	Activity	Planned model years	Total resource cost
Tco95 AMIP	AMIP runs for model sensitivity, retuning AMIP, development runs AMIP	1300	12,350,000 SBU
Tco95/eORCA1	Coupled runs for model sensitivity, coupled retuning, coupled development testing, testing new cycle	1000	17,000,000 SBU
Tco199 AMIP	AMIP runs for model sensitivity, retuning AMIP	1200	56,400,000 SBU
Tco199/eORCA1	Testing new cycle	250	14,125,000 SBU

Total in 2022: 99,875,000 SBU

2023:

Model resolution	Activity	Planned model years	Total resource cost
Tco95 AMIP	Retuning AMIP, development runs AMIP	300	2,850,000 SBU
Tco95/eORCA1	Coupled development testing	500	8,500,000 SBU
Tco199 AMIP	Retuning AMIP, Development runs AMIP	300	14,100,000 SBU
Tco199/eORCA1	Coupled development testing	500	28,250,000 SBU
Tco319 AMIP	AMIP runs for model sensitivity, AMIP tuning	340	59,500,000 SBU

Total in 2023: 113,200,000 SBU

2024:

Model resolution	Activity	Planned model years	Total resource cost
Tco95 AMIP	Retuning AMIP, development runs AMIP	300	2,850,000 SBU

Tco95/eORCA1	coupled development testing	500	8,500,000 SBU
Tco199 AMIP	Retuning AMIP, Development runs AMIP	300	14,100,000 SBU
Tco199/eORCA1	Coupled development testing, long coupled run	1500	84,750,000 SBU
Tco319/eORCA025	Development testing	100	28,250,000 SBU

Total in 2024: 138,450,000 SBU

Storage resources

We estimate a need for at least 30TB in the first year for storage of needed initial conditions, boundary conditions and validation datasets. The output of selected development runs will need to be stored and preserved for comparison with other experiments in all years, together with the output of longer coupled tuning and development runs with the full model. However, the introduction of the XIOS server also for processing oIFS data will considerably reduce the amount of required output, considering that will be no longer necessary to store 6-hourly grib files. We estimate a need for storing about 1200 model years every year (at resolutions Tco95 and Tco199) at a cost of 50 GB/model year for output at both resolutions (10 GB/y and 40 GB/y respectively), for a total of about 60TB additionally each year. A planned 100y run at Tco319 in 2024 will add another 15TB. While most of the storage requested at ECMWF will be needed for the development process during the project, a fraction of the stored experiments and postprocessing output will be transferred to local resources at the participating institutions at the end of the project for further investigation and to be used as initial conditions for new experiments.

We expect that in the period 2022-2024 a great number of additional computing and storage resources, in excess to those provided by this special project, will be needed in order to allow tuning and testing of the full EC-Earth4 model, particularly at higher resolutions and in coupled mode. These additional resources will be secured through applications to international HPC programmes (such as PRACE) and through national resources provided by consortium partners with their own resources.

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