SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	EC-EARTH4: developing a next-generation European Earth System model based on ECMWF modelling systems
Computer Project Account:	SPNLTUNE
Start Year - End Year :	2022 - 2024
Principal Investigator(s)	Shuting Yang
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project aims at supporting the development of configurations of the next generation of the EC-Earth global Earth-system model: EC-Earth4, based on OpenIFS and NEMO4. In particular the project will allow model experiments to be used in the tuning process, including AMIP runs aimed at determining atmospheric model sensitivity to parameter changes, validation and testing of the model following the integration of new component cycles, experiments aimed at testing new parameterizations and new configurations and long coupled equilibrium experiments at intermediate resolution to assess model biases and to tune ocean parameters. Experiments with different model resolutions and different component configurations are planned. The activity will include the implementation of a continuous testing, tuning and software validation framework.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Due to a longer than expected development cycle, the release of a GCM version of EC-Earth4, suitable for tuning and a first evaluation of biases occurred only during summer 2024. In particular EC-Earth4-GCM needs the implementation of CMIP6 forcings and of M7 aerosols in OpenIFS and the development of the aerosol component has led to unforeseen delays in the planned schedule, leading to a planned complete ESM version of EC-Earth4 becoming available only during 2025.

We have also noted that EC-Earth4 is significantly slower than EC-Earth3 and also that EC-Earth4 is slower on HPC2020 than on other HPCs such as “Freja” at NSC in Sweden. For this reason, early long test experiments were done on “Freja” at NSC in Sweden rather than HPC2020. We found that the slowdown in EC-Earth4 compared to EC-Earth3 was due to the upgrade from IFS 36r4 to OpenIFS 48r1 and mostly due to a more frequent call to the radiation module. We note that EC-Earth4 is faster than EC-Earth3 when OpenIFS 48r1 runs in single precision. The cause for slower execution of EC-Earth4 on HPC2020 compared to some other HPCs is not yet clear, but could be due to the relatively older hardware on HPC2020 (2nd gen AMD chips etc).

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

No particular issues were encountered, all procedures appear efficient and the overall experience was very positive.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Development of EC-Earth 4

The EC-Earth climate model has undergone substantial development in the past three years, marked by three key releases—EC-Earth 4.0.0, 4.0.1, and 4.1.0. These iterations reflect the transition to a more modern, flexible modeling system ready for CMIP7 protocols and capable of supporting a broader range of scientific experiments and computational platforms. SPNLTUNE resources were used during development for testing, benchmarking and tuning the model, integrated by additional computing resources provided by consortium members on their machines.

EC-Earth 4.0.0

EC-Earth 4.0.0, the first official release of the EC-Earth 4 generation, released in mid-2024, was primarily designed as a prototype for model familiarization, technical validation, and early tuning. It marked the transition to newer core components including OpenIFS-43r3 for the atmospheric model, NEMO 4.2.2 for the ocean component, and OASIS3-MCT 5.2 for coupling, along with XIOS 2.5+ for efficient I/O management.

This initial version supported both atmosphere-only and coupled atmosphere-ocean (GCM) configurations. While a wide range of atmospheric resolutions—from low-resolution Tl63L31 to high-resolution Tco399L91—were technically supported, only selected resolutions (Tco95, Tl159, Tl255) were long-run tested and accompanied by initial condition datasets. On the ocean side, the eORCA1 grid was adopted as the standard configuration, offering improved representation of ocean processes in the Southern Ocean through its extended domain.

Forcing datasets such as greenhouse gases, solar irradiance, and ozone followed CMIP6 standards. While CMIP6-style metadata and native-grid NetCDF output were already implemented, some limitations remained—such as the lack of support for ocean-only simulations out-of-the-box and limited machine portability.

EC-Earth 4.0.1

The release of EC-Earth 4.0.1 at the beginning of 2025 represented a major consolidation and extension of the model's capabilities, still with cy43r3, in preparation for a following switch to cy48r1. It retained the same core components but introduced broader support for model configurations, including ocean-only simulations (with or without biogeochemistry) and fully coupled models with inert tracers. This was a critical step toward enabling a wider range of experiments such as AMIP, OMIP, and CMIP-class simulations.

Support for ocean grids was expanded to include ORCA1 and ORCA2 alongside eORCA1, although only eORCA1 underwent full validation, and ORCA1 support is expected to be phased out. The same comprehensive set of atmospheric resolutions was retained, and long-run stability continued to be demonstrated for Tco95, Tl159, and Tl255 configurations.

A major addition was the integration of monitoring tools and the ECmean4 post-processing framework, facilitating easier evaluation of model performance. Furthermore, the model was successfully ported to a broader range of HPC systems across several European centers, including Marenostrum 5 (BSC), HPC2020 (ECMWF), and clusters at NSC and CSC, with the HPC2020 as the test bed for the consortium. These efforts improved the model's accessibility and robustness in operational and research contexts.

Despite this progress, some challenges persisted. Not all high-resolution atmospheric configurations were suitable for production runs, often requiring additional tuning or suffering from numerical instability. The TL63ORCA2 configuration, for example, was eventually abandoned due to unsustainable memory demands in long simulations.

EC-Earth 4.1.0

EC-Earth 4.1.0, released in spring 2025 but developed already during all of 2024, marks a major milestone in the model's evolution, as it introduces the latest version of the atmospheric component (OpenIFS-48r1). This upgrade represents a fundamental modernization of the EC-Earth system, aligning the model with the newest developments in the ECMWF OpenIFS codebase. OpenIFS-48r1 includes a number of scientific and technical improvements over its predecessor (OpenIFS-43r3), such as updated physics packages - in particular the hydrological cycle of the model, improved numerics, and enhanced scalability on modern HPC architectures. Importantly, this transition required a full revalidation of model performance and interoperability, as well as adaptations to the model infrastructure and dependencies.

The ocean component remains based on NEMO 4.2.2, but have upgraded with some major bugfixed from the NEMO consortium. The model continues to support multiple horizontal grids—eORCA1, ORCA2, and ORCA1—though eORCA1 is still the only resolution fully validated. In terms of configurations, EC-Earth 4.1.0 maintains the same range of supported modes as 4.0: Atmosphere-only (AMIP), Ocean-only (OMIP), with or without biogeochemistry and/or inert tracers, Fully coupled atmosphere-ocean (AOGCM) configurations, also with optional biogeochemistry and tracers.

However, because of the substantial internal changes brought by OpenIFS-48r1, the number of atmospheric configurations that have been fully tested is currently limited. Long-run initial conditions are provided only for the Tl159L91 and Tl255L91 resolutions. Some exploratory runs have been reported at Tco95 and even Tco1279, but these remain technically unsupported for operational or production use due to a lack of stability testing and input data.

Tuning / evaluation tools

Several software tools were implemented and adapted to EC-Earth during development in order to validate, monitor and tune the model. Implementation was developed on HPC2020 using SPNLTUNE resources.

Automatic monitoring

An online monitoring system which provides basic timeseries figures and global maps for monitoring of experiments has been implemented and can be activated directly in scriptengine (SE) jobs, uploading figures directly to the EC-Earth gitlab portal.

EC-Mean

ECmean4 is a lightweight parallelized tool for evaluation of basic properties of Global Climate Models, such as global mean and climate model performance indices with comparisons to a number of observational data sets. It was inspired by the original ECmean scripts which were developed for EC-Earth2 and EC-Earth3 evaluation, but it uses Python3 to perform lazy calls with Xarray+Dask and makes use of YML configuration files, with parallelization support with Multiprocess. It works both on raw EC-Earth4 output and on CMOR model output from CMIP5 and CMIP6. The main ECmean4 repository is available on github with complete documentation. ECmean support was added to EC-Earth4 scriptengine, allowing to run it directly and automatically in a EC-Earth4 job.

AQUA

AQUA (Application for QUality Assessment) is a model evaluation framework designed for running diagnostics on high-resolution climate models, developed for the Destination Earth Climate Adaptation Digital Twin. It provides a flexible and efficient python3 framework to process and analyze large volumes of climate data and it includes several diagnostics needed to monitor and validate climate experiments. It is available as a public repository on github. It was adapted to run with EC-Earth4 data providing a suitable catalog generator and implementing the needed fixes and grids, see the dedicated repository.

ECTuner

ECtuner is an automatic atmospheric tuning tool written in python developed for EC-Earth4. This atmospheric tuning tool uses ECmean output files to compute new suggested values for EC-Earth OIFS parameters, based on radiative flux sensitivities determined from AMIP sensitivity tests. The suggested parameters are written in yaml format, ready for inclusion in a SE job.

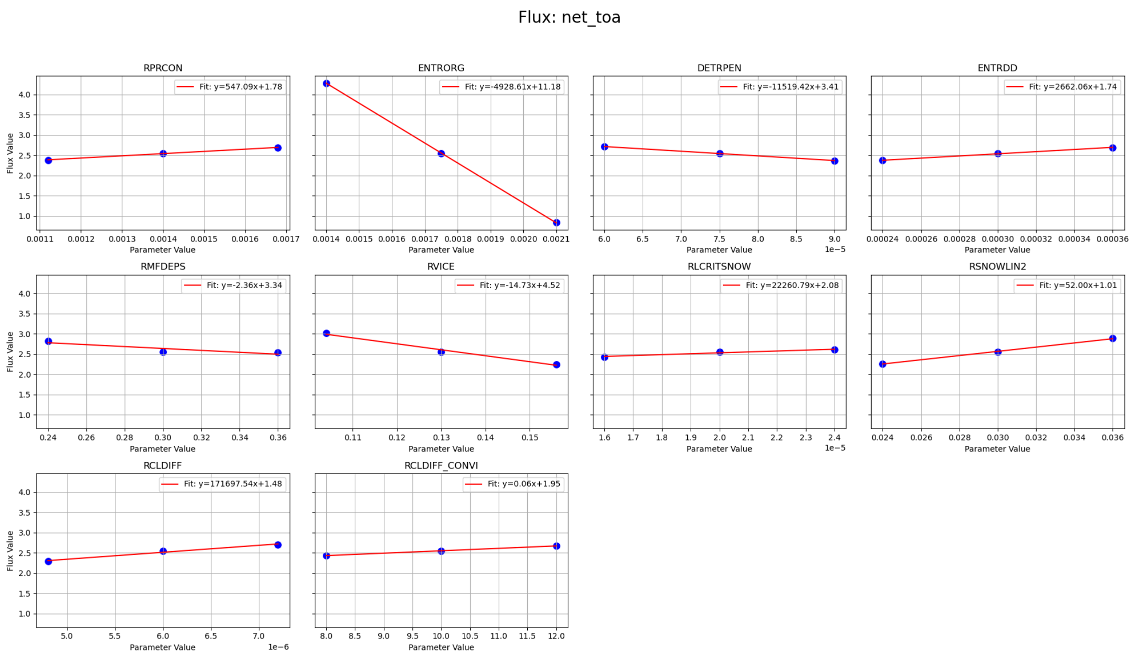
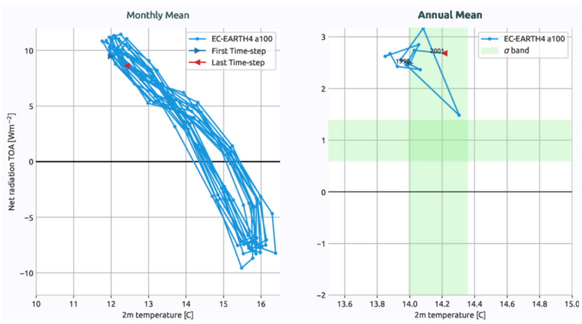


Figure 1. Sensitivity of Net TOA radiative flux to changes in tuning parameters.

Development tests for EC-Earth4

AMIP sensitivity

After identifying a list of relevant tuning parameters of interest (mainly convective and microphysical), an ensemble of AMIP experiments was run varying tuning parameter values by +/- 20% compared to defaults, to assess the sensitivities of radiative fluxes in the model (shortwave and longwave fluxes at surface and TOA, including cloud radiative forcing). This exercise was performed both for EC-Earth 4.0.1 and 4.1.0. As an example, Fig. 1 reports the resulting sensitivities for net TOA radiative flux. After running an initial baseline AMIP run for the years 1990-2001 (the first year was not considered for tuning), using these sensitivities and the ECtuner automatic tuning tool, new alternative tuning parameter sets were obtained (differing in the weight given to tropical areas). This strategy allows to quickly tune the atmospheric component of the model. As an example, Fig. 2 reports Gregory plots for two 11-year long AMIP experiments: a baseline run (left) and after automatic parameter tuning (right). The figure clearly shows that the initial radiative imbalance was corrected by the tuning procedure. Global biases shown in Fig. 3 are encouraging, even if clearly there is still room for further improvement.

a) 

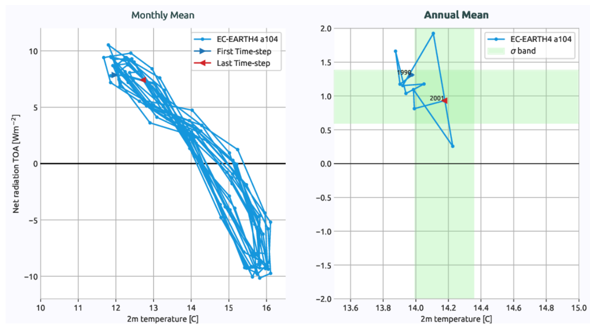
b) 

Figure 2. Gregory plot of EC-Earth4 experiments with ERA5 2m temperature and CERES net TOA radiative flux as reference (green shadings); (a) baseline; (b) tuned experiment. Plots produced by AQUA.

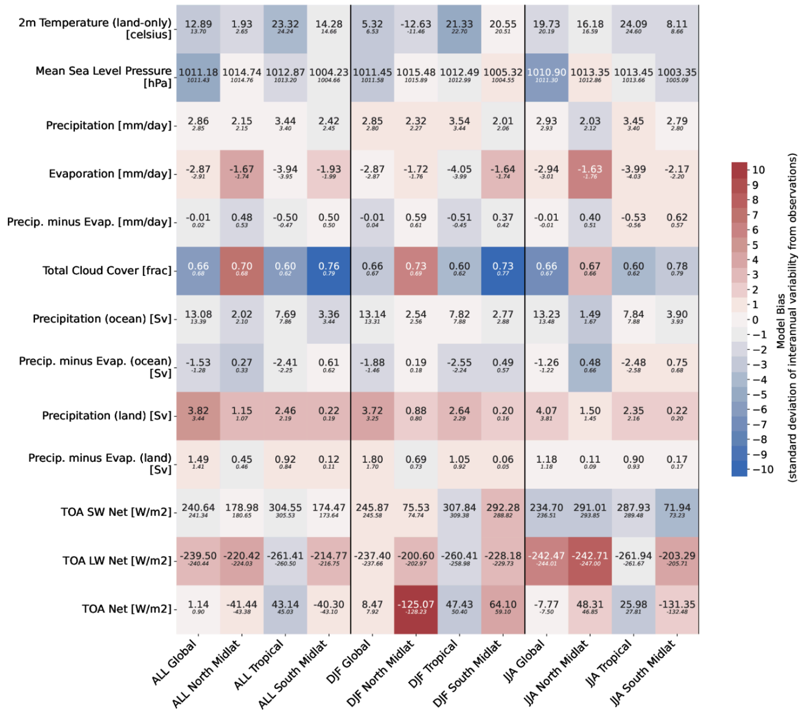


Figure 3: Global and regional biases of tuned EC-Earth4 AMIP simulation computed by ECmean

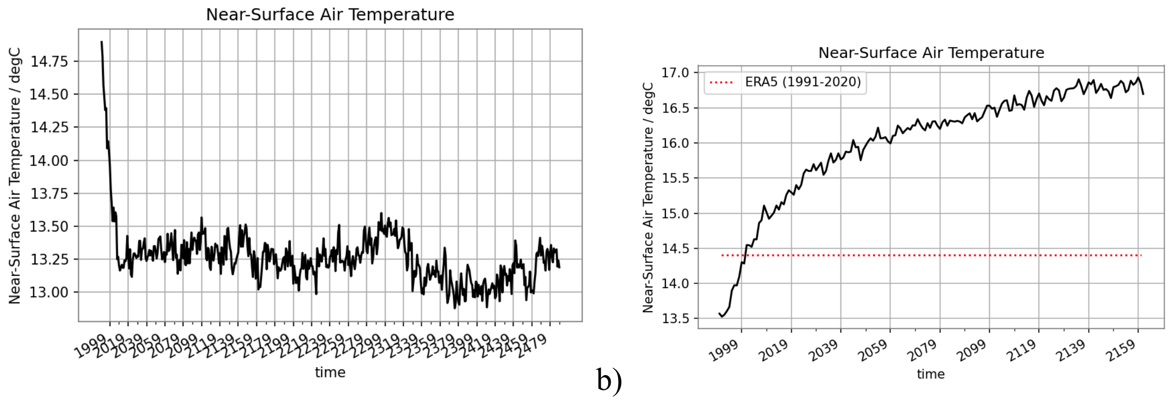


Figure 4: Long coupled integrations with present-day forcing with EC-Earth4 at TL255 resolution. a) v4.0.1 (IFS cy43r3); b) v4.1.0 (IFS cy48r1)

Long coupled runs

Long coupled runs of EC-Earth4 both for present day (PD; forcing fixed at 1990 level) and pre-industrial (PI; 1850 forcing) are regularly performed for all releases of EC-Earth4 to serve as a basis for tuning efforts, using also computing resources provided by consortium partners. Comparison of runs performed with v4.0.1 (using IFS cy43r3), see Fig. 4a, with v4.1.0 (using IFS cy48r1), see Fig. 4b, shows that the recent version is characterized by an important temperature bias which will be a primary target for model tuning in 2025.

Testing Supercooled liquid water for cy43r3

A long-standing climate model bias is the Southern Ocean warm bias. At ECMWF, in IFS cycle 45 a change was made by Richard Forbes to improve the representation of supercooled liquid water. This improvement was not included in the EC-Earth version before the transition from cycle 43r3 to cycle 48r1. The change was backported into cycle 43r3 and two 30 year coupled EC-Earth simulations starting from Levitus climatology were performed, one with the standard cy43r3 code, and one with the supercooled liquid water treatment. While in the initial 10 years the Southern Ocean Sea ice simulation has been improved, in the longer term (years 11-30 of the simulation) no clear improvement has been seen when evaluating across a range of parameters, probably because the model was not yet tuned. The encouraging result is that the shortwave cloud forcing proved to be clearly better especially in the Southern Hemisphere. In the new EC-Earth version 4.1 that is based on OpenIFS cycle 48r1, the supercooled liquid water parameterisation is implemented, and further tuning efforts will be based on this version.

Scaling tests on HPC2020 (early 2024)

The EC-Earth4 model was installed and scale-tested on HPC2020 using the intel compilers and intel-openmpi. The EC-Earth4 AOGCM configuration comprised the following components: OpenIFS 43r3v2, NEMO 4.2.0, XIOS 2.5+ and OASIS3-MCT 5.2. The system was tested using standard MPI and hybrid MPI-OpenMP (implemented within OpenIFS). Fig. 5 presents timings for a one-month simulation. In all runs, the number of cores for XIOS was set to 1. For each node, numerous different allocations of cores between OpenIFS and NEMO were tested to quantify the optimal balancing of cores between model components. The figure presents the optimal timing for each node. The higher resolution versions of EC-Earth v4 were not available for testing at the time of the scaling experiments and new scaling tests will be needed with the final model version before starting CMIP7 production runs.

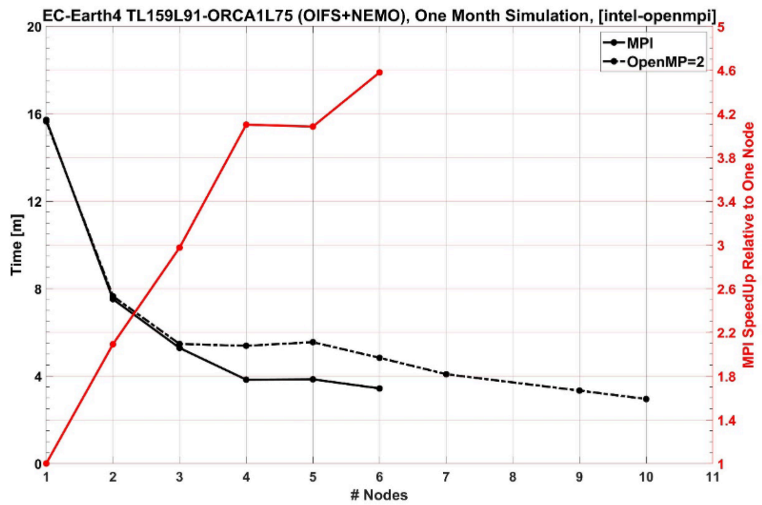


Figure 5. EC-Earth4 TL159L91-ORACA1L75 timings for a one-month simulation.

Paleoclimate developments

A range of experiments was performed with EC-Earth4 and EC-Earth3 (used as a baseline) in preparation of CMIP7 PMIP.

EC-Earth4 FastTrack Abrupt-127k

According to the PMIP4 protocol, we have conducted fast-track simulations for abrupt-127k and piControl using EC-Earth4_oifs-43r3v2 at TL159 resolution. The experiments have been run for 460 years (lig127k) and 429 years (piControl) to investigate Last Interglacial climate characteristics.

The EC-Earth4 FastTrack abrupt-127k and piControl experiments have not yet reached climate equilibrium, even after more than 400 years of simulation, showing a significant downward trend in temperature. Compared to EC-Earth3, the Arctic warming amplification during the Last Interglacial (LIG) period is much weaker, deviating from previous results. Additionally, the Antarctic region exhibits abnormally low sea ice coverage, which was unexpected and requires further tuning (Fig. 6).

Last Interglacial sea level sensitivity experiments

To assess the climatic impact of sea level rise during the LIG, we performed a series of idealized experiments using EC-Earth3-Veg-LR with prescribed global mean sea level increases of 5 m and 10 m relative to the present-day. These simulations isolate the effects of bathymetric change while keeping other forcings constant.

Compared to PI, the LIG experiments with or without sea level rise show significant changes in ocean circulation and surface temperature. In particular, sea level rise leads to a freshening of the North Atlantic and salinity increase in the Southern Ocean, contributing to a strengthened Atlantic Meridional Overturning Circulation (AMOC; Fig. 7). Despite the enhanced AMOC, the +5 m and +10 m experiments exhibit overall cooler surface temperatures compared to the LIG simulation without sea level rise, indicating that sea level rise alone can introduce a net cooling effect.

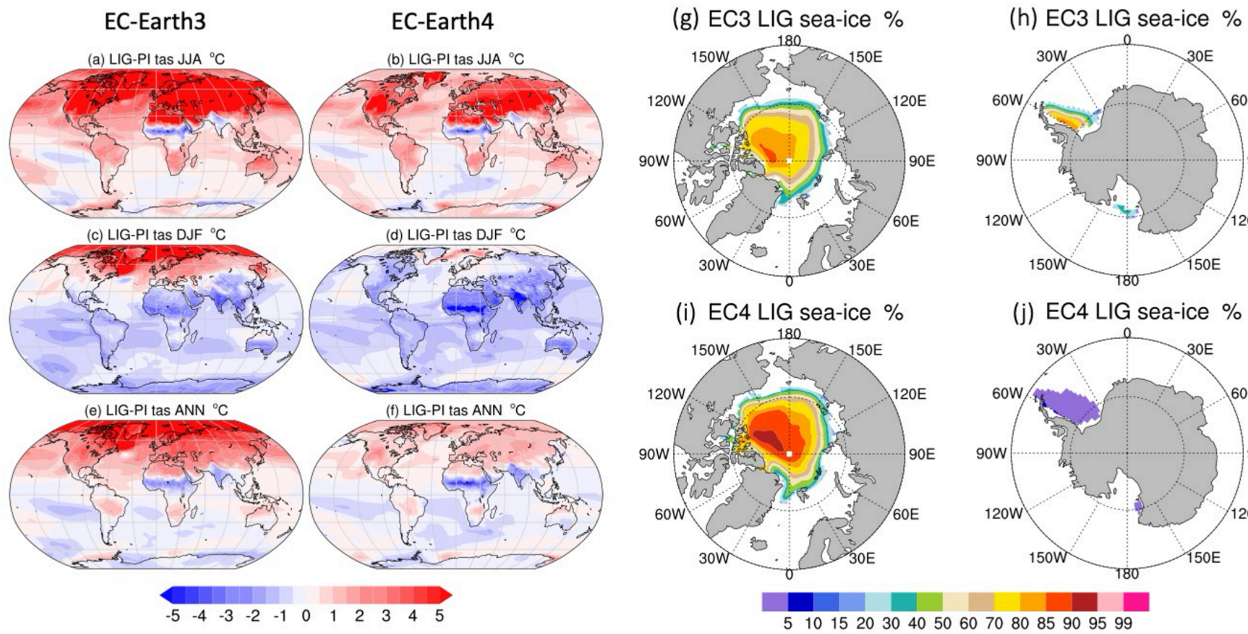


Figure 6: EC-Earth3 and EC-Earth4 simulated surface temperature anomalies (°C) for the Last Interglacial (LIG) relative to the PI period in summer (JJA), winter (DJF), and annual mean (ANN), and sea ice concentration (%) in the Arctic and Antarctic.

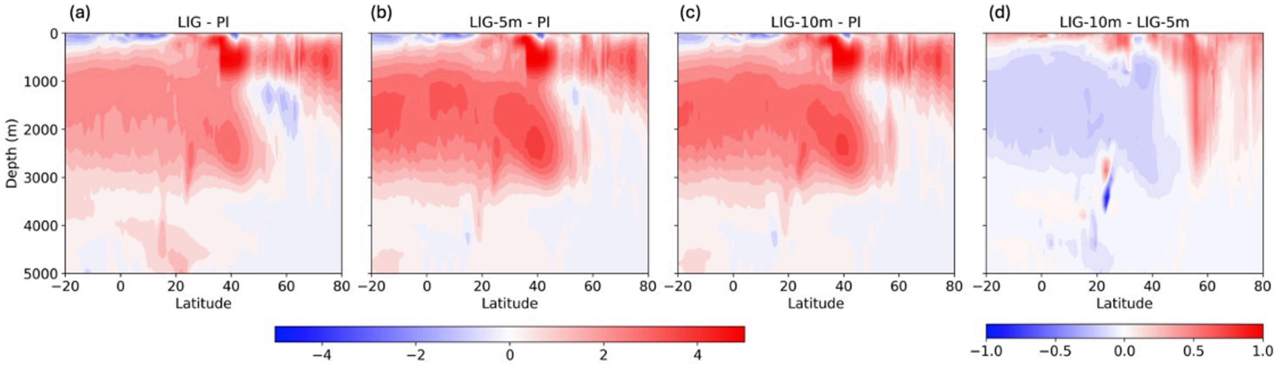


Figure 7: AMOC anomalies of LIG (a), LIG+5 m (b), and LIG+10 m (c) relative to the pre-industrial (PI) simulation. The rightmost panel shows the difference between LIG+10 m and LIG+5 m (d).

These results emphasize that sea level change—through its influence on bathymetry, coastline geometry, and oceanic pathways—can substantially reshape both circulation and climate, even in the absence of changes in external forcings. Sea level must therefore be considered a key boundary condition in paleoclimate modeling frameworks and future CMIP7 experimental designs.

Ocean Biogeochemical Modelling Towards EC-Earth4

The upgrade from EC-Earth3 to EC-Earth4 does not include significant changes to the representation of the ocean carbon cycle. The core ocean biogeochemical component, **PISCESv2**, remains unchanged between the two model versions. However, several updates on the physical side — such as the upgrade of the ocean model to **NEMO4.2** — can indirectly influence the biogeochemical dynamics, including ocean carbon uptake.

Given the high computational cost of running the biogeochemical component, conducting a series of preparatory simulations using EC-Earth3 was essential before transitioning to EC-Earth4. These simulations enabled the evaluation of model performance, verification of the stability and accuracy of key biogeochemical processes, and refinement of various model configurations and initialisation strategies.

This preparatory work facilitated the validation of critical developments and diagnostics and improved the interpretation of ocean biogeochemistry and carbon dynamics outputs. The experience and insights gained from EC-Earth3 have been directly applied to EC-Earth4, ensuring an efficient and scientifically sound transition. As a result, the supercomputing hours allocated to EC-Earth4 have been used more effectively.

CO_2 Fluxes (1985–2014)

A spatial analysis of modelled CO_2 fluxes from 1985 to 2014, compared with estimates from the Global Carbon Budget, reveals that the model captures distinct regional patterns of CO_2 uptake (Fig. 8). These patterns are closely linked to deep-water formation regions, driven by large-scale ocean circulation. In polar regions, for instance, denser surface waters sink into the deep ocean, carrying dissolved carbon with them. Additionally, lower temperatures at high latitudes enhance the solubility of atmospheric CO_2, increasing the efficiency of oceanic carbon uptake.

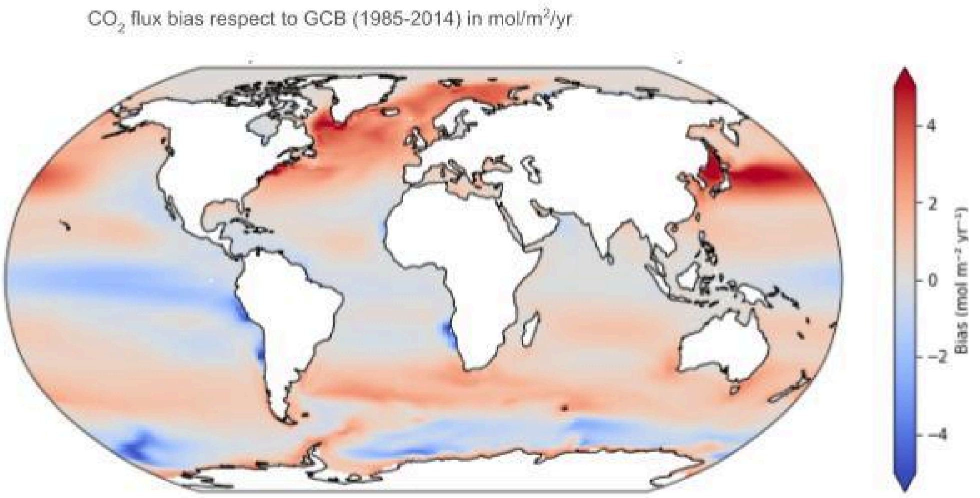


Figure 8: Climatological biases over 1985-2014 of the global carbon fluxes from an ensemble of 5 members of e-driven historical runs from EC-Earth3-CC run with SPNLTUNE hours. Positive values mean fluxes into the ocean. The bias has been calculated with respect to the ensemble of observational products from the Global Carbon Budget initiative.

Surface Chlorophyll (1998-2014)

The same ensemble of five EC-Earth3-CC simulations used for the CO_2 flux analysis was also evaluated for surface chlorophyll concentration. Model output was compared with the ESA OC-CCI observational product (version 6), as shown in Fig. 9. This comparison helps assess the realism of simulated primary production and phytoplankton biomass.

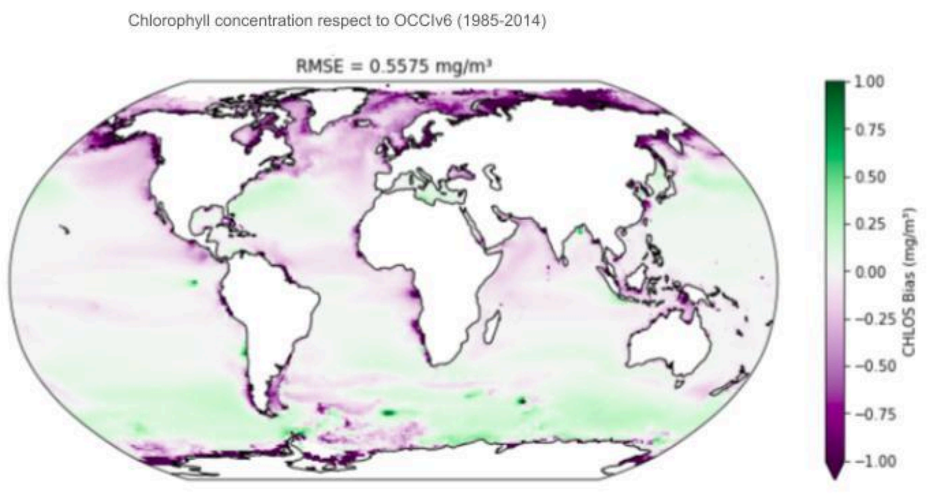


Figure 9: Bias of Surface Chlorophyll from an ensemble of 5 members of e-driven historical runs with respect to the observations from the ESA occc-vi, version 6.

List of publications/reports from the project with complete references

1. Lu, Z., Schultze, A., Carré, M., Brierley, C., Hopcroft, P. O., Zhao, D., Zheng M., Braconnot P., Yin Q., Jungclaus J., Shi X., Yang H., Zhang Q.: Increased frequency of multi-year El Niño–Southern Oscillation events across the Holocene, *Nature Geoscience*, 18, 337–343, https://doi.org/10.1038/s41561-025-01670-y, 2025.
2. Wang Z., Zhang Q., Chen J., Han Z.: Differential Vegetation Feedback on the Global Land Monsoon System during the Mid-Holocene and Last Interglacial. *Advances in Atmospheric Sciences*, https://doi.org/10.1007/s00376-024-4284-6, 2025.
3. Power, K. and Zhang, Q.: The impacts of reduced ice sheets, vegetation, and elevated CO2 on future Arctic climates. Arctic, *Antarctic, and Alpine Research*, 56(1), 2433860. https://doi.org/10.1080/15230430.2024.2433860, 2024.
4. Gaetani, M., Messori, G., Pausata, F. S. R., Tiwari, S., Alvarez Castro, M. C., and Zhang, Q.: Mid-Holocene climate at mid-latitudes: assessing the impact of Saharan greening, *Clim. Past*, 20, 1735–1759, https://doi.org/10.5194/cp-20-1735-2024, 2024.
5. Berntell, E., Zhang, Q.: Mid-Holocene West African monsoon rainfall enhanced in EC-Earth simulation with dynamic vegetation feedback. *Clim Dyn*, https://doi.org/10.1007/s00382-024-07262-7, 2024.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

A continuation of this project for 2025-2027 has been granted.

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 including the atmospheric chemistry and aerosol module M7) + 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).

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.