SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2024
Project Title:	EC-EARTH4: developing a next-generation European Earth System model based on ECMWF modelling systems
Computer Project Account:	SPNLTUNE
Principal Investigator(s):	Shuting Yang
Affiliation:	Danish Meteorological Institute
Name of ECMWF scientist(s) collaborating to the project (if applicable)	……
Start date of the project:	01/01/2022
Expected end date:	31/12/2024

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	115,000,000	47,986,252	140,000,000	9,340,840
Data storage capacity	(Gbytes)	150,000	3111	225,000	3,111

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 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 (10 lines max)

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 is now planned 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.

Summary of plans for the continuation of the project (10 lines max)

The release of a tagged GCM configuration of EC-Earth4, to serve as a baseline for tuning and further development, including OpenIFS cy43r3v2 and NEMO 4.2.0 is now expected to be released in June 2024. An experimental OpenIFS cy48r1 version is being tested with the goal of substituting the current version next year. Implementation of LPJ-Guess 4.2 is planned. Some of the planned experiments (still this year) include:

- New long Present Day and Pre-Industrial control/reference runs are planned with the tagged GCM version of the model (500 years each).
- A range of AMIP tuning experiments to assess model radiative fluxes sensitivity to tuning parameter changes has to be performed with the tagged model revision issued this summer.
- Implementation of a semi-automatic testing suite, with standard experiments being run at each major merge to the model main code with automatic evaluation of biases using the ECMean4 tool.
- Test PlioMIP3 simulations with Pliocene land-sea mask and updated boundary conditions following PlioMIP protocol and implementing new forcings for the last millennium and past 2000 years (Past2k).

List of publications/reports from the project with complete references

1. Chen, J., Zhang, Q., Lu, Z., Duan, Y., Cao, X., Huang, J., and Chen, F.: Reconciling East Asia's mid-Holocene temperature discrepancy through vegetation-climate feedback, *Science Bulletin*, https://doi.org/10.1016/j.scib.2024.04.012, 2024.
2. Han, Z., Power, K., Li, G., and Zhang, Q.: Impacts of mid-Pliocene ice sheets and vegetation on Afro-Asian summer monsoon rainfall revealed by EC-Earth Simulations, *Geophysical Research Letters*, 51, e2023GL106145, https://doi.org/10.1029/2023GL106145, 2024.
3. Cao, N., Zhang, Q., Power, K., Schenk, F., Wyser, K., and Yang, H.: The role of internal feedbacks in sustaining multi-centennial variability of the Atlantic Meridional Overturning Circulation revealed by EC-Earth3-LR simulations. *Earth and Planetary Science Letters, 621,* https://doi.org/10.1016/j.epsl.2023.118372, 2023.
4. Tian, Y., Fleitmann, D., Zhang, Q., Sha, L., Wassenburg, J., Axelsson, J., Zhang, H., Li, X., Hu., J., Li, H., ZHao, L., Cai, Y., Ning, Y., and Cheng, H.: Holocene climate change in southern Oman deciphered by speleothem records and climate model simulations. *Nat Commun* **14**, 4718, https://doi.org/10.1038/s41467-023-40454-z, 2023.

Summary of results

*If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.*

The development of EC-Earth4 in the past year has led to a current version, supporting both atmosphere-only and coupled experiments, with OpenIFS cy43r3, Nemo 4.2 with eORCA1 grid. The following CMIP6 forcings have been implemented: solar, O3, GHG. Land use and aerosol forcings are still missing. A new tool rdy2cpl ("ready to couple") allows to generate grids, areas, masks and namelist files needed by the Oasis coupler and computes remapping weights on the fly. Further activities performed in the framework of the project and sustained by the availability of SPNLTUNE resources include:

- The supercooled liquid water treatment that was operational from cycle 45 (developed by Richard Forbes, ECMWF) was backported into the OpenIFS cycle43r3v2 version of EC-Earth4 (this is a port originally developed for AWI-CM3) and tested in a series of simulations.
- Adjustments to cloud and convection parameters are being tested.
- Simulations were performed to test Tco199 resolution and the appearance of Gibbs wiggles (ringing).
- A new modal aerosol scheme has been implemented based on the M7 (Vignati et al., 2004) code from the Hamburg Aerosol Module (HAM) (Tegen et al., 2019). We started this development in OpenIFS 43r3 and have continuously been performing short test simulations to evaluate the aerosol simulation with regard to concentrations, optical properties and global budgets. Porting to the latest OpenIFS release based on IFS cycle 48r1 has started towards the end of 2023. Tests are currently being carried out with this version.
- We have spent some efforts to adopt the EC-Earth4 prototype model to Atos and performed a number of scaling tests using the intel compilers and intel-openmpi to investigate the computational efficiency and the load balance.
- We are actively preparing and testing for the PlioMIP and PMIP standard experiments. Due to the requirement to fit the new Land-Sea Mask, we have regenerated the initial conditions and created new forcing files for the mid-Pliocene Warm Period (~3.3–3.0 million years ago) and other Paleo-time periods required by PMIP. To determine what fraction of the variability is due to external forcing and what fraction reflects purely internal variability, we have conducted Last Millennium

experiments. We prepared the input files for these experiments and successfully ran an 850 CE equilibrium experiment (completed 389 years) and a transient simulation (currently ran 227 years).

- In parallel to the development and activities related to the EC-Earth4 version some experiments and tests have been performed with a post-CMIP6 version of EC-Earth3 as preparatory for future implementations. In particular, some years of an historical simulation have been produced and cmorized. Considering the configuration of the EC-Earth3 version used that include new components, like coupling with Arctic ice-sheet and Antarctica freshwater fluxes, this experience gained can be highly useful for forthcoming tuning of the EC-Earth4 stable version.

Cited references:

Vignati, E., Wilson, J., and Stier, P.: M7: An efficient size-resolved aerosol microphysics module for large-scale aerosol transport models, J. Geophys. Res., 109, D22202, https://doi.org/10.1029/2003JD004485, 2004.

Tegen, I., Neubauer, D., Ferrachat, S., Siegenthaler-Le Drian, C., Bey, I., Schutgens, N., Stier, P., Watson-Parris, D., Stanelle, T., Schmidt, H., Rast, S., Kokkola, H., Schultz, M., Schroeder, S., Daskalakis, N., Barthel, S., Heinold, B., and Lohmann, U.: The global aerosol–climate model ECHAM6.3–HAM2.3 – Part 1: Aerosol evaluation, Geosci. Model Dev., 12, 1643–1677, https://doi.org/10.5194/gmd-12-1643-2019, 2019.