REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: Denmark

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Principal Investigator[1]: Chuncheng Guo

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Project Title:

Emission-driven Earth System projections and multi-century overshoot extensions with EC-Earth4: AMOC-ice sheet interactions and reversibility for CMIP7

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.)	2027	
Would you accept support for 1 year only, if necessary?	YES	

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	80,000,000	80,000,000	80,000,000
Graphics Processing Unit Cluster-A	[GBU]	-	-	-
Graphics Processing Unit Cluster-B	[GBU]	-	-	-
Accumulated data storage (total archive volume)[2]	[GB]	30,000	30,000	30,000

[1] The Principal Investigator will act as contact person for this EMI R&D 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.

EWC resources required for project year:		2027	2028	2029
Number of vCPUs	[#]	-	-	-
Total memory	[GB]	-	-	-
Storage	[GB]	-	-	-
Number of vGPUs[3]	[#]	-	-	-

Continue overleaf.

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Extended abstract

1. Scientific plan

1.1 Motivation and scientific objectives

The central scientific question of this project is **the evolution and reversibility of the coupled ocean-ice sheet system under realistic, emission-driven forcing on multi-century timescales**. The Atlantic Meridional Overturning Circulation (AMOC) and the polar ice sheets are among the climate system's most consequential potential tipping elements, and their coupling — through both Greenland and Antarctic meltwater fluxes — governs whether warming-induced changes can be reversed if emissions decline. Climate models agree on AMOC weakening under anthropogenic forcing, but the timing, amplitude, and crucially the reversibility of that response remain deeply uncertain (IPCC; Ben-Yami et al., 2024; van Westen et al., 2024). Our recent work (Guo et al., 2026) demonstrating **reversible AMOC despite continued — and irreversible — Greenland Ice Sheet (GrIS) melt under idealised forcing** motivates the obvious next step: testing that **resilience under the realistic, policy-relevant emission pathways in the multi-century horizons as now defined by CMIP7**. A weakening or even collapse of the AMOC can severely affect European climate and weather patterns, including regional temperature and precipitation, whereas melting ice sheets can have global repercussions in sea level rise.

The new CMIP7 ScenarioMIP design (Van Vuuren et al., 2026) makes this assessment particularly timely. Within a coordinated framework, the ScenarioMIP prescribes emission-driven simulations as the default, allowing carbon-cycle feedbacks to shape the realised forcing (Sanderson et al., 2024), and it defines long-term extensions to 2500 AD, explicitly to explore long-term Earth-system dynamics in response to warming at different temperature levels — including the risk of reaching tipping points and triggering large-scale irreversible changes — and to probe reversibility under different long-term net-negative emissions pathways. These extensions, and the high-overshoot trajectories among them, are precisely the experiments needed to investigate AMOC-ice sheet reversibility. Such understanding has been missing from the existing literature because 1) most modelling groups run the standard scenarios only to 2100 or 2150, and 2) very few climate models can interactively couple the Greenland and, especially, the Antarctic Ice Sheet. This project is designed to address both gaps.

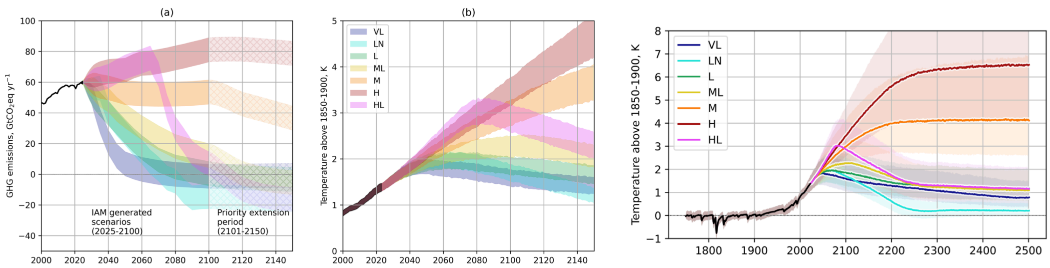

Fig. 1 CMIP7 scenarios showing greenhouse gas emissions pathways (left), and the associated estimates of global average temperature until 2150 (middle) and extension to 2500 (right). Figures from van Vuuren et al. (2026).

The specific objectives are:

1. Multi-century AMOC-ice sheet trajectories. Quantify GrIS mass-balance evolution and AMOC strength and structure under high, overshoot, and very-low pathways through to 2500 AD, using the interactively coupled EC-Earth4-ESM with PISM.
2. Reversibility and hysteresis. Determine whether, and under what pathways, AMOC and ice-sheet states may recover along overshoot (peak-and-decline) pathways — contrasting these against monotonic warming and stabilisation-only pathways.
3. Carbon-cycle-coupled forcing realism. Exploit the emission-driven configuration to characterise how climate-carbon cycle feedbacks modulate the forcing actually experienced by the ocean and ice sheets.
4. Production-quality bipolar ice-sheet coupling. Consolidate the existing coupling framework for the interactive Greenland and Antarctic ice sheets within EC-Earth4, working on the validation of the dual configuration. We will include dynamic Antarctic evolution in the long simulations to study its tipping behaviour, interactions with AMOC and GrIS evolution, and links with other tipping elements, in coordination with the ISMIP7 ESM-ISM working group (www.ismip.org).

1.2 Model configuration

The EC-Earth models have contributed to a number of CMIP6 experiments (Hazeleger et al, 2012; Doscher et al., 2022). In this project, experiments will be based on its latest Earth system model configuration EC-Earth4-ESM for CMIP7 (https://ec-earth.org/ec-earth/ec-earth4/): OpenIFS (cy48r1) atmosphere/land, NEMO 4.2 with SI3 sea ice, LPJ-GUESS dynamic vegetation, the PISM model for interactive ice sheets, and the M7 modal aerosol scheme, coupled through OASIS3-MCT with XIOS parallel I/O and CMOR-compliant output. The standard atmosphere/ocean resolutions are TL255L91/ORCA1. The model will be run in CO2 emission-driven mode. An interactive Greenland ice sheet is already an established component of EC-Earth simulations, and an interactive Antarctic ice sheet is implemented and currently under active testing. This project will focus on bringing the bipolar coupled configuration to production quality and used for multi-century applications.

1.3 Experiment design

The experiment set follows the CMIP7 ScenarioMIP protocol (Van Vuuren et al., 2026). An emission-driven historical simulation over 1850-2021 is the starting point. From here we run a scenario set spanning the plausible range — Very Low (VL), High-to-Low (HL), Low-to-Negative (LN), and High (H) — over 2022-2150, and then the scientifically central component: the Tier-1 long extensions to 2500 AD for H and VL (as the protocol requests), plus the Tier-2 overshoot extensions HL-ext and LN-ext to 2500, chosen specifically to maximise information on AMOC and GrIS hysteresis under peak-and-decline forcing.

Scenario rationale: VL and H are the protocol's Tier-1 extension pair ("as low as plausible" and "as high as plausible"), bracketing the outcome space. The project's scientific focus on reversibility rests on a set of overshoot pathways extended to 2500: HL follows the High trajectory before a sharp mid-century turn to net-zero CO2; LN reaches the Paris Agreement target through a higher peak followed by very large-scale carbon removal — the protocol's most extreme "climate reversal" pathway, sustaining net-negative emissions to return temperatures toward near-preindustrial levels from 2300 onward (whereas VL constrains the overshoot to the smallest plausible level). Together, VL-ext, HL-ext and LN-ext span increasing overshoot magnitude and carbon-removal intensity, providing the cleanest available test of path dependence and hysteresis in the coupled climate-ice sheet system. The emphasis of the request is deliberately on the post-2100 extensions and overshoot dynamics — the part of the protocol most groups will not cover, and the part that directly serves this project's objective of studying evolution and reversibility of the climate tipping elements. The historical and 2022-2150 scenario runs are the necessary parent states from which the extensions branch, not the scientific deliverable in themselves.

1.4 Community value and collaboration

The long-extension and overshoot ESM simulations are scarce: they are needed by the ice-sheet, sea-level, tipping-point, and climate impact communities, which lack ESM-driven multi-century overshoot trajectories to force, train, and evaluate against. By coupling an interactive ice sheet model (PISM) into these long runs, EC-Earth4-ESM provides exactly the climate-ice sheet coupled, emission-driven, multi-century output that multiple groups are interested in, including the broader tipping-element and early-warning-signal communities.

A developmental strand of the project works toward coupling the Antarctic Ice Sheet within EC-Earth4 and including it in the long simulations, opening the study of bipolar ice-sheet dynamics, AIS tipping, and interactions among tipping elements within a single Earth system model — an area of substantial and growing scientific interest. While Greenland coupling is already implemented and central to the planned experiments, the Antarctic component, with its coupling framework already existing at DMI, will be further refined and tested within this project and is pursued in coordination with the ISMIP7 ESM working group. The project is led and carried out at DMI, building directly on the institute's established expertise in EC-Earth development, AMOC reversibility, and climate-ice sheet coupling and interactions. The model outputs are of broad interest and will be made available to the general scientific community through CMIP7/ESGF.

2. Justification of resources

2.1 Costing basis

For the standard EC-Earth4-ESM configuration (at TL255/eORCA1 grid and single precision), it costs ~80,000 SBU per model year. The estimate uses the latest M7 benchmark information from the EC-Earth tuning project SPNLTUNE, which indicates that M7 is the dominant cost driver relative to MACv2SP. We budget conservatively at ~80k SBU per model-year for the full emission-driven ESM configuration including aerosols, dual ice sheets, I/O, and other operational needs. In total, we plan to run 3000 model years, which amount to 240,000,000 SBUs (see details below).

2.2 Experiment details

Experiment	Model years	Mem	mil. SBU	Notes
esm-hist (1850-2021)	172	1	14	All runs emission-driven
esm-VL (2022–2150)	129	1	10	Tier-1 low
esm-LN (2022–2150)	129	1	10	Tier-1 deep overshoot
esm-HL (2022–2150)	129	1	10	Tier-1 overshoot
esm-H (2022–2150)	129	1	10	Tier-1 high
esm-VL-ext (2151–2500)	350	1	28	Tier-1 extension
esm-LN-ext (2151–2500)	350	1	28	Tier-2 climate reversal, hysteresis
esm-H-ext (2151–2500)	350	1	28	Tier-1 extension
esm-HL-ext (2151–2500)	350	1	28	Tier-2 overshoot, hysteresis
Coupled Antarctic ice sheet consolidation and production runs	900		72	Selected runs with dual ice sheets
TOTAL	3000		240	

2.3 Annual phasing

Project year	2027	2028	2029
SBU	80 M	80 M	80 M
Main activity	esm-hist, scenarios until 2150; AIS integration	Scenario extensions to 2500; AIS consolidation	Scenario extensions to 2500; AIS production

2.4 Storage strategy

Output is transferred continuously to local DMI storage as each simulation completes, rather than accumulated on ECMWF disks and tapes. Cmorisation and ESGF data publication will also be handled locally at DMI. The ECFS/MARS request therefore covers only a modest rolling working set. This keeps the ECMWF storage and archive footprint low and reflects the actual data-management workflow.

3. Technical characteristics of the code

EC-Earth4 couples ECMWF's OpenIFS (cy48r1), NEMO 4.2/SI3, LPJ-GUESS, PISM, and M7 through OASIS3-MCT, with XIOS-based parallel I/O. The model has already been ported, optimised, and tuned on the Atos HPCF under the SPNLTUNE project. Dedicated HPC2020 platform configurations and automated Slurm launch modes via the ScriptEngine runtime environment make ECMWF's HPCF the natural production platform for EC-Earth4. Running on HPCF provides direct, low-latency access to the input4MIPs forcing data. The model can run efficiently at modest node counts at TL255/ORCA1; throughput, parallel decomposition, and I/O have been validated during CMIP7 preparation. Our tests give us concrete operational confidence in the HPC workflow, and the requested production budget is conservatively based on our current M7 aerosol cost estimates.

4. Relationship to existing projects and acknowledgement

This project is complementary to and non-overlapping with the SPNLTUNE project (led by Shuting Yang from DMI), which develops and tunes EC-Earth4; whereas this project uses the tuned, production-ready coupled ESM to perform defined CMIP7 multi-century scenario experiments. No model development or tuning resources are requested here. Outputs will acknowledge ECMWF computing facilities, will be published openly on ESGF, and will be reported in the annual EMI R&D progress reports.

5. Key references

IPCC, Climate Change (2021): The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. V. Masson-Delmotte et Al.) (Cambridge University Press, Cambridge and New York; https://doi.org/10.1017/9781009157896).

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