LATE REQUEST FOR A EMI R&D PROJECT 2026–2028

Country/Organisation: Netherlands/KNMI

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Project Title: Interactive Antarctic Freshwater Feedbacks in EC-Earth4 using the Antarctic Ice Melt Emulator (AIME)

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.)	2026	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Late EMI R&D Projects are normally approved for 1 year, but exceptionally can be approved for 3 years.

Computer resources required for project year:		**2026**	**2027**	**2028**
High Performance Computing Facility	[SBU]	30,000,000	15,000,000	
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	70,000	105,000	

EWC resources required for project year:		**2026**	**2027**	**2028**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

[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.

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Extended abstract

All EMI R&D 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 EMI R&D 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 EMI R&D 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).

Overview

The long-term evolution of the climate system depends critically on interactions between greenhouse gas forcing, the Southern Ocean, and the Antarctic Ice Sheet (Fyke et al., 2018; Holland et al., 2020; Mackie et al., 2020b; Li, 2022; Sadai et al., 2025). Increasing ocean temperatures around Antarctica enhance ice-shelf basal melting, leading to increased freshwater input into the Southern Ocean. This freshwater modifies upper-ocean stratification, reshapes global ocean heat uptake patterns, and promotes subsurface heat accumulation where it can further enhance ice-shelf melting. These interconnected processes constitute one of the largest uncertainties in projections of future climate and sea-level change (Siahaan et al., 2022; Park et al., 2023).

This project will exploit the newly developed coupling between EC-Earth4 Earth-system model (EC-Earth4-ESM) and the Antarctic Ice Melt Emulator (AIME) to investigate the coupled evolution of climate, Southern Ocean circulation, and Antarctic freshwater forcing from the present day until 2150. AIME represents Antarctic ice-sheet mass loss through linear response functions derived from comprehensive ice-sheet model simulations (Levermann et al., 2020; van der Linden et al., 2023), allowing freshwater forcing to evolve consistently with changing ocean conditions at a fraction of the cost of a fully coupled ice-sheet model.

The use of the EC-Earth4-ESM configuration will allow identification and quantification of the impact of Antarctic freshwater forcing on physical ocean circulation and heat uptake, as well as Southern Ocean stratification, nutrient supply, primary productivity, air-sea CO_2 exchange, ocean carbon uptake and sea level changes. The inclusion of Earth system components allows the project to also assess whether Antarctic meltwater feedbacks modify the capacity of the Southern Ocean to absorb heat and carbon under contrasting greenhouse gas pathways.

The project will investigate future climate evolution under both very low-emission (SSP1-2.6 or equivalent) and high-emission (SSP3-7.0 or equivalent) scenarios, combined with low- and high-sensitivity Antarctic ice-sheet response functions (representing current inter-model spread). These simulations will quantify uncertainties associated with future meltwater discharge and assess how Antarctic freshwater forcing will modify Southern Ocean stratification, subsurface ocean warming, surface cooling, sea-ice evolution, and global heat uptake over centennial-scale timescales in a warming climate.

In addition, targeted process-oriented experiments using Lagrangian iceberg discharge and a three-equation ice-shelf basal melting parameterisation will be performed to investigate how these processes, including the changes in iceberg pathways, evolve under climate warming and to provide guidance for improving future versions of AIME. Together, these experiments will provide a physically based framework for assessing Antarctic climate-ice-sheet feedbacks while supporting the development of ice-sheet emulators for Earth System Models.

1. Scientific Background

The Antarctic Ice Sheet is expected to become an increasingly important driver of future climate evolution through the release of freshwater into the Southern Ocean. Freshening of the surface ocean increases upper-ocean stratification, suppresses bottom water formation, and modifies the vertical distribution of ocean heat (Pauling et al., 2016; Bronselaer et al., 2018; Golledge et al., 2019). While surface cooling and expanded sea ice may partially offset global warming

(Bronselaer et al., 2018; Purich and England, 2023; Sadai et al., 2020; Mistry et al., 2025), reduced vertical mixing promotes subsurface ocean warming at depths corresponding to Antarctic ice shelves. This warming enhances basal melting, creating a positive feedback that can further accelerate ice-sheet mass loss (Pritchard et al., 2012; Rignot et al., 2019).

Current CMIP6-class simulations either neglect these feedbacks or prescribe freshwater forcing independently from climate evolution. As a result, uncertainties remain regarding the magnitude of Southern Ocean feedbacks, their influence on global ocean circulation and sea ice, and their interaction with greenhouse gas forcing over centennial timescales.

There is a need to include more realistic, dynamically evolving freshwater forcing in comprehensive climate models without the computational expense of fully coupled ice-sheet simulations. The Antarctic Ice Melt Emulator (AIME) provides such a framework by translating subsurface ocean temperature anomalies into freshwater discharge using linear response functions derived from state-of-the-art ice-sheet model simulations, calibrated against observations of basal melt.

Coupling AIME with EC-Earth4 enables systematic investigation of long-term climate projections in which freshwater forcing evolves consistently with climate change while remaining computationally efficient enough for multi-century ensemble experiments.

Incorporating Lagrangian iceberg models could improve the realism of freshwater delivery even further by explicitly resolving iceberg pathways and melt, which strongly influence upper-ocean stratification, sea ice processes, and regional circulation (Martin and Adcroft, 2010; Marsh et al., 2015; Zhang et al., 2025). Moreover, EC-Earth4 does explicitly resolve ice-shelf cavities (Mathiot et al., 2017) offering promising avenues for improving ocean-ice coupling in future EC-Earth4 simulations.

2. Scientific Objectives

The project addresses five primary scientific objectives.

Objective 1: Quantify the impact of dynamically evolving Antarctic freshwater forcing on long-term climate projections under contrasting greenhouse gas forcing pathways.

Objective 2: Assess the uncertainty associated with Antarctic ice-sheet sensitivity by comparing simulations using low- and high-sensitivity linear response functions derived from ice-sheet models.

Objective 3: Investigate feedbacks between Southern Ocean stratification, subsurface ocean warming, Antarctic Bottom Water formation, sea-ice evolution, and large-scale ocean circulation.

Objective 4: Evaluate process-based representations of Antarctic freshwater release through Lagrangian iceberg transport and three-equation ice-shelf basal melting, and use these experiments to inform future development of the Antarctic Ice Melt Emulator.

Objective 5: Quantify the impact of Antarctic freshwater forcing on Southern Ocean biogeochemistry and carbon uptake, including changes in stratification, nutrient redistribution, primary productivity, air-sea CO_2 exchange, and ocean carbon storage.

3. Experimental Design

3.1. Model description

In this project, we will utilize the Earth system model EC-Earth4 v4.1.8. Depending on ongoing model development and tuning considerations, the final component activation may be adjusted from the baseline configuration. This configuration leverages OpenIFS 48r1 for atmospheric physics and dynamics and couples it with NEMO 4.2.2 for ocean circulation. Sea-ice processes are handled by the SI3 module within NEMO, providing comprehensive thermodynamic and dynamic representation of sea ice. Advanced land-ice coupling including the Antarctic Ice Melt Emulator (AIME) and the dynamic ice sheet model PISM will support improved cryosphere-ocean interaction studies. Ocean biogeochemistry may include PISCES, subject to configuration compatibility, to simulate marine nutrient cycling, phytoplankton dynamics, and carbon fluxes between the atmosphere and ocean interior. All components communicate through OASIS3-MCT 5.2 for flux exchange, with XIOS 3.0 managing parallel I/O operations.

Specifically, we will configure EC-Earth4-ESM coupled to AIME and, where feasible, PISCES, enabling analysis of both physical and carbon-cycle responses to Antarctic freshwater forcing depending on the selected configuration. AIME provides computationally efficient freshwater forcing through linear response functions derived from comprehensive Antarctic ice sheet model simulations. The coupling requires the exchange of subsurface ocean temperature anomalies from EC-Earth4-ESM to AIME and freshwater fluxes from AIME back to the ocean model. Because AIME evaluates linear response functions rather than solving the full ice dynamics equations, the additional computational overhead remains negligible compared with the full ESM integration.

The ESM configuration including PISCES is preferred over the AOGCM configuration because Antarctic freshwater forcing and associated changes in the ocean can alter biological productivity and air-sea CO_2 exchange. These feedbacks cannot be assessed with an AOGCM-only configuration. The simulations will therefore provide a physically and biogeochemically consistent framework for evaluating Antarctic freshwater feedbacks under future climate change, with final component selections finalized after development benchmarks and tuning assessments are completed (expected in September 2026).

3.2. Main projections experiments

The main projection experiments will combine two greenhouse gas forcing pathways: one representing a very low-emission future (SSP1-2.6 or CMIP7 equivalent), and another representing a high-emission future (SSP3-7.0 or CMIP7 equivalent), with strong warming. For each scenario, simulations will be performed with low- and high-sensitivity AIME response functions, representing current intermodel spread. This results in four principal transient simulations extending from present-day to the year 2150 (Table 1). An additional control simulation without interactive freshwater forcing will provide a baseline against which the climatic effects of Antarctic meltwater feedbacks can be quantified.

These simulations will use the latest EC-Earth4-ESM configuration, including the coupled atmosphere, ocean, sea-ice, land and marine biogeochemistry components, together with the Antarctic Ice Melt Emulator (AIME). The emulator receives subsurface ocean temperature anomalies from EC-Earth4 and computes freshwater discharge around Antarctica through linear response functions representing Antarctic ice-sheet sensitivity. The use of the ESM configuration extends the scope of the project to assess both the physical climate response and the associated biogeochemical ocean feedbacks arising from Antarctic freshwater forcing.

Model output will include atmosphere, ocean, sea-ice, freshwater and marine biogeochemistry diagnostics required to analyse changes in circulation, heat uptake, carbon uptake, nutrient redistribution, primary production, and cryosphere-ocean interactions.

Table 1. Model experiments

Experiment	Scenario	Antarctic freshwater representation	Years	Simulated years
Control	SSP1-2.6	No interactive freshwater	1980-2150	170
EXP1	SSP1-2.6	AIME: Low sensitivity	1980-2150	170
EXP2	SSP1-2.6	AIME: High sensitivity	1980-2150	170
EXP3	SSP3-7.0	AIME: Low sensitivity	1980-2150	170
EXP4	SSP3-7.0	AIME: High sensitivity	1980-2150	170
EXP5	SSP3-7.0	Lagrangian icebergs	1980-2150	170
EXP6	SSP3-7.0	3EQ basal melting	1980-2150	170
Development & testing	–	Coupling, testing, debugging	–	70
Total				1,260 years

3.3. Process-oriented sensitivity experiments

To complement the main projection experiments, we will perform a series of targeted process-oriented simulations aimed at improving the physical representation of Antarctic freshwater forcing in EC-Earth4 and guiding future developments of AIME. Additional process-oriented experiments using Lagrangian iceberg forcing and three-equation basal melting will be conducted under SSP3-7.0 or equivalent scenario, where the Antarctic melt signal is expected to be strongest.

The first set of experiments will evaluate Lagrangian iceberg discharge, in which solid ice discharge is represented by drifting icebergs, advected by the ocean currents and the wind, rather than being instantaneously converted into Southern Ocean freshwater fluxes. This approach allows freshwater to be released gradually along iceberg trajectories, providing a more realistic spatial and temporal distribution of freshwater input into the Southern Ocean. The simulations will assess how iceberg transport influences upper-ocean stratification, sea-ice evolution, subsurface ocean warming, nutrient availability and primary production, and Antarctic Bottom Water formation under different greenhouse gas forcing scenarios.

A second set of experiments will investigate the implementation of a three-equation (3EQ) thermodynamic parameterisation for ice-shelf basal melting. These simulations will evaluate how basal melting evolves under future warming and how it differs from the parameterisations currently represented through AIME response functions.

The results from these process experiments will provide a physically based benchmark for the emulator. In particular, they will help identify where additional complexity, such as spatially and temporally evolving iceberg melt or improved representations of ocean-driven basal melting, could be incorporated into future generations of AIME response functions and coupling.

4. Expected Scientific Outcomes

The project will deliver multi-century climate projections using EC-Earth4 with interactive Antarctic freshwater forcing based on an ice-sheet emulator.

The simulations will provide:

- Quantitative estimates of uncertainty arising from Antarctic ice-sheet sensitivity.
- Improved understanding of feedbacks between meltwater input, ocean stratification and subsurface warming.
- Assessment of how freshwater forcing modifies global ocean circulation under different greenhouse gas pathways.
- Evaluation of long-term climate feedbacks extending from 1980 until 2150.
- A benchmark dataset for future CMIP7 analyses and tipping-element research.

The resulting simulations will contribute directly to understanding climate risks associated with Antarctic ice-sheet evolution.

5. Justification of Computational Resources

The proposed project requires computational resources to perform a suite of long-term coupled climate simulations covering the period 1980-2150. The experimental design consists of a control simulation, four production simulations using the Antarctic Ice Melt Emulator (AIME), two process-oriented sensitivity experiments using the NEMO Lagrangian iceberg module (ICB) and a three-equation (3EQ) ice-shelf basal melting parameterisation, together with dedicated development and testing runs.

The production experiments use the EC-Earth4 configuration. This configuration is required to quantify not only the physical response of Southern Ocean circulation and heat uptake, but also the associated biogeochemical and carbon-cycle feedbacks. The EC-Earth4-AOGCM costs about 26,000 SBU per simulated year. The computational overhead associated with AIME is negligible because the emulator evaluates pre-computed linear response functions rather than explicitly solving ice-sheet dynamics. The additional cost of PISCES is estimated to increase the cost by 33% relative to the AOGCM configuration, resulting in 35,000 SBU per simulated model year. The additional cost of the NEMO-ICB module is expected to remain modest (approximately 10-15% relative to the standard EC-Earth4 configuration; resulting in ca. 39,000 SBU per simulated model year). A computational cost of 37,000 SBU per simulated model year is assumed for development runs (Table 2).

Table 2: Estimated computational resources

Activity	Simulated years	Estimated SBU / year	Estimated SBU
Control simulation	170	35,000	5.95 M
AIME experiments	680	35,000	23.80 M
Lagrangian iceberg experiment	170	39,000	6.63 M
3EQ basal melting experiment	170	35,000	5.95 M
Development & testing	70	37,000	2.59 M
Total	**1,260**		**45 M SBU**

Our simulations will generate 1,260 total simulated years of Earth system model output, representing an aggregate computational load of roughly 45 million SBU. This workload has been partitioned into two sequential execution windows: (i) Primary CMIP-aligned projection experiments allocating 30 million SBU in 2026, and (ii) Targeted sensitivity and methodology refinement experiments requiring 15 million SBU in 2027.

Storage requirements are dominated by monthly three-dimensional ocean diagnostics together with standard atmosphere, sea-ice and surface fields required to analyse Antarctic Bottom Water formation, freshwater transport, ocean heat uptake and climate feedbacks. Output frequency has been optimised to minimise archive volume while retaining all diagnostics required for the scientific objectives. Additional storage is allocated for restart files, model development, and sensitivity experiments (Table 3).

Table 3: Estimated storage requirements

Activity	Simulated years	Estimated storage / year	Estimated storage
Control simulation	170	75 GB	12.75 TB
AIME experiments	680	75 GB	51.0 TB
Lagrangian iceberg experiment	170	85 GB	14.45 TB
3EQ basal melting experiment	170	75 GB	12.75 TB
Development & testing	70	75 GB	5.25 TB
Safety margin / restart files	-	-	8 TB
Total requested storage	**1,260**		**105 TB**

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