

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

**Country/Organisation:** Italy

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**Project Title:** Bipolar Ice-Sheet Freshwater Forcing and Ocean Circulation Stability (BIOCS)

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 <input checked="" type="checkbox"/>	

To make changes to an existing project please submit an amended version of the original form.  
Late EMI R&D Projects are normally approved for 1 year, but exceptionally can be approved for 3 years.

<b>Computer resources required for project year:</b>	<b>2026</b>	<b>2027</b>	<b>2028</b>
High Performance Computing Facility [SBU]	25,000,000 SBU	25,000,000 SBU	
Graphics Processing Unit Cluster-A [GBU]			
Graphics Processing Unit Cluster-B [GBU]			
Accumulated data storage (total archive volume) <sup>2</sup> [GB]	48TB	96TB	

<b>EWC resources required for project year:</b>	<b>2026</b>	<b>2027</b>	<b>2028</b>
Number of vCPUs [#]			
Total memory [GB]			
Storage [GB]			
Number of vGPUs <sup>3</sup> [#]			

<sup>1</sup> 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.

<sup>2</sup> 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.

<sup>3</sup>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

This project investigates the response of global ocean circulation to freshwater input from the Greenland and Antarctic ice sheets under anthropogenic climate change. Increasing ice-sheet mass loss is expected to freshen the North Atlantic and Southern Ocean, weakening deep and bottom water formation and potentially altering the Atlantic Meridional Overturning Circulation and the Southern Meridional Overturning Circulation. While these hemispheric responses have been studied separately, their combined effects and possible inter-hemispheric interactions remain poorly constrained.

Using the EC-Earth3-ESM Earth System Model, the project performs a coordinated set of idealised multi-century simulations as part of a novel Model Intercomparison Project. The proposed set up combines greenhouse gas-driven warming with freshwater forcing from one or both ice-sheets and includes transient, equilibrium, and reversal phases to assess circulation sensitivity, stability thresholds, and reversibility of the coupled climate system.

The model output produced under this project will be shared with the climate community to support analysis of ocean circulation stability, carbon-cycle feedbacks, and tipping-point behaviour. The outcomes are expected to directly support the Intergovernmental Panel on Climate Change Seventh Assessment Report, particularly in the assessment of abrupt climate change, tipping points, and high-impact events.

## 1. Introduction

### 1.1 Scientific Context

The Greenland and Antarctic ice sheets are experiencing accelerating mass loss driven by anthropogenic climate change, resulting in increasing freshwater fluxes into the North Atlantic and Southern Ocean, respectively. These freshwater inputs, combined with ongoing surface ocean warming, modify upper-ocean buoyancy forcing and stratification. In the North Atlantic, the resulting reduction in surface water density weakens deep convection in regions that are key for the formation of North Atlantic Deep Water. This process is expected to slow down the Atlantic Meridional Overturning Circulation (AMOC), with model projections indicating a robust weakening

over the 21st century and the possibility of abrupt transitions or collapse under sustained high-emission scenarios and strong freshwater forcing.

In the Southern Ocean, enhanced meltwater discharge from the Antarctic Ice Sheet similarly strengthens upper-ocean stratification by freshening and stabilising the surface layer. This leads to a complex set of responses in which reduced vertical mixing yields a redistribution of heat over the water column, that cools at the surface and warms over the subsurface. This is associated with positive feedback: surface cooling promotes sea ice growth, which further isolates the ocean from the atmosphere and drives subsurface heat accumulation at the depths where ice shelf basal melt is strongest, ultimately reinforcing melt and potentially destabilising ice streams and accelerating ice-sheet mass loss. A key consequence of these coupled processes is a reduction in the formation of Antarctic Bottom Water, which is a critical component of the global abyssal circulation.

Within this context, the concept of a Southern Meridional Overturning Circulation (SMOC) has been used to describe the large-scale overturning structure in the Southern Ocean. A recent study by Baker et al. (2025) suggests that the Southern Ocean provides a dynamical constraint that makes a complete AMOC collapse harder than many simple conceptual models suggest. Therefore, a better understanding and estimates of the Southern Ocean circulation is urgently needed to accurately predict future AMOC change. Model studies suggest that the SMOC may weaken substantially under strong freshwater forcing, although its precise definition, variability, and long-term stability remain uncertain compared to the better-constrained AMOC.

Despite significant progress in understanding the individual hemispheric responses, the combined effects of concurrent freshwater forcing from Greenland and Antarctica on the global overturning circulation remain poorly constrained. Indications of inter-hemispheric interactions have been found in intermediate complexity models (Siné et al., 2025), but they are not studied in complex climate models or Earth System Models. In particular, the nonlinear interactions between AMOC and SMOC, and their potential coupling through interhemispheric heat and freshwater transport, are not yet fully understood. Important open questions remain regarding how these circulation changes affect the efficiency of oceanic carbon uptake, the likelihood of crossing critical thresholds, and the potential for cascading tipping elements within the Earth system, including feedbacks involving the cryosphere, ocean circulation, and the global carbon cycle.

## **1.2 Current status**

In recent years, several coordinated multi-model efforts have been developed to improve the understanding of the impacts of ice-sheet mass loss on ocean circulation stability and potential tipping behaviour. These initiatives have primarily focused on quantifying the response of the Atlantic Meridional Overturning Circulation (AMOC) and Southern Ocean overturning to idealised freshwater perturbations.

A prominent example is the North Atlantic Hosing Model Intercomparison Project (NAHosMIP; Jackson et al., 2023), which investigates the stability of the AMOC under a constant and strong freshwater forcing applied to the North Atlantic and Arctic regions. The experiments are conducted under pre-industrial boundary conditions, providing a simplified background state to isolate the ocean circulation response to freshwater perturbations and to assess the existence of stability thresholds in the AMOC.

A complementary effort is the Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative (Swart et al., 2023), which focuses on the climatic response to Antarctic meltwater discharge. SOFIA experiments aim to quantify the spatial pattern, magnitude, and dynamical consequences of freshwater forcing in the Southern Ocean, including impacts on stratification, sea-ice cover, bottom water formation, and the Southern Ocean overturning circulation. These experiments provide key

insight into regional feedbacks associated with Antarctic ice-sheet mass loss and its role in the global climate system.

More recently, the Tipping Points Modelling Intercomparison Project (TIPMIP; Winkelmann et al., 2025) has been established to explicitly investigate threshold behaviour and irreversibility in the Earth system. Its ocean domain, TIPMIP-OCEAN, (Swingedouw et al., 2026), extends previous hosing experiments by combining freshwater perturbations with anthropogenic greenhouse gas forcing. The experimental design includes idealised pathways of increasing atmospheric CO<sub>2</sub> concentrations, stabilization, and potential reversal, alongside freshwater inputs in the North Atlantic. This combined-forcing setup enables investigation of the interactions between global warming and freshwater fluxes. The simulations are currently being performed across participating modelling centres, and data will be available toward the end of 2026.

However, model experiments considering the combined forcing of global warming and freshwater input in the Southern Ocean due to the Antarctic ice sheet melting, are not considered in TIPMIP-OCEAN. Moreover, a comprehensive assessment of the coupled impacts of simultaneous freshwater input from both the Greenland and Antarctic ice sheets remains largely unexplored in a coordinated intercomparison project. In particular, the potential for interhemispheric interactions between freshwater perturbations, and their combined influence on the AMOC, SMOC, and global ocean carbon uptake, has not yet been systematically assessed across an ensemble of state-of-the-art ESMs.

To address this gap, the scientific community is currently preparing a dedicated Model Intercomparison Project focusing on a) experiments combining overshoot scenarios for both CO<sub>2</sub> and freshwater input in the Southern Ocean, and b) combined bipolar freshwater forcing experiments. Such an initiative is expected to provide critical insight into the nonlinearity and reversibility of the response of the global ocean circulation system under combined future meltwater fluxes. The outcomes will be highly relevant for the Intergovernmental Panel on Climate Change (IPCC) Seventh Assessment Report (AR7), which will include, for the first time, a dedicated chapter on abrupt changes, low-likelihood high-impact events, and tipping points in the Earth system. In this context, the timely development of coordinated protocols and the execution of multi-model simulations are essential to meet the assessment timelines of AR7 and to improve the robustness of projections of future ocean circulation stability.

### ***1.3 Objective and expected contributions to the field***

Building on our previous participation to NAHOSMIP, SOFIA and TIPMIP-OCEAN with EC-Earth3 and EC-Earth3-ESM, the main objective of this special project is to contribute to a Model Intercomparison Project aimed at improving the understanding of the response of global ocean circulation to ice sheet-driven freshwater input under anthropogenic climate change. In particular, the project will focus on two complementary scientific questions.

First, we aim to investigate the combined effects of Southern Ocean freshening and ongoing greenhouse gas-driven global warming on the stability of the Southern Meridional Overturning Circulation. This aspect builds on and extends existing coordinated experiments in SOFIA and TIPMIP-OCEAN, by explicitly targeting the reversibility of global warming-driven changes of the circulation in the Southern Ocean and the associated feedbacks on heat and carbon uptake.

Second, the project will assess the impact of simultaneous freshwater input from both the Greenland and Antarctic ice sheets under a global warming background state. This will allow for a systematic evaluation of potential inter-hemispheric interactions between freshwater perturbations and their combined influence on the Atlantic Meridional Overturning Circulation, Southern Meridional Overturning Circulation, and the global overturning circulation. Of particular

interest are the possibility of nonlinear responses, threshold behaviours, and cascading effects within the coupled ocean–cryosphere system.

All simulations produced within this project will be made available to the broader climate modelling and impacts community in a timely and standardised manner. The data will allow a wide range of analyses, including assessments of circulation stability, climate feedbacks, and carbon cycle responses. These outputs are expected to provide a key contribution to the scientific basis for the IPCC AR7, particularly in the context of abrupt changes, tipping points, and high-impact climate outcomes.

## **2. Methodology**

### **2.1 The Earth System Model**

The model to be used is the EC-Earth3-ESM (Döscher et al., 2022), a fully coupled Earth System Model developed by the European EC-Earth Consortium for participation in the Coupled Model Intercomparison Project Phase 6 and 7. EC-Earth3-ESM extends the physical climate system representation of EC-Earth3 by including interactive vegetation, biogeochemistry and cryosphere components, enabling a comprehensive simulation of coupled atmosphere–ocean–land–ice–carbon interactions.

It couples the ECMWF atmosphere-land model (IFS cycle 36r4) with the NEMO (version 3.6) model for the ocean and sea ice components (LIM3 model). Terrestrial ecosystem dynamics are represented by the LPJ-GUESS dynamic vegetation model, while marine biogeochemistry is simulated using the PISCES ocean biogeochemical model. Ice-sheet processes are represented using the Parallel Ice Sheet Model (PISM), allowing for interactive coupling between climate and ice-sheet evolution for the Greenland Ice Sheet. The Antarctic Ice Sheet, on the contrary, is not coupled interactively, but freshwater fluxes in response to increased ocean temperatures are included through the Antarctic Ice Melt Emulator. Carbon-cycle feedbacks are closed through a simplified atmospheric CO<sub>2</sub> representation (“co2box”), which mediates exchanges of carbon between the land, ocean, and atmosphere reservoirs.

This modelling framework is particularly well suited to investigate climate feedbacks associated with ice-sheet mass loss, ocean circulation changes, and carbon-cycle interactions, as it explicitly resolves the coupled dynamics of the climate system, cryosphere, and biogeochemical cycles.

### **2.2 The experiments**

The aim is to complement the TIPMIP-OCEAN by two additional experiments:

A. Freshwater hosing in the Southern Ocean within global warming (total of 600 years):

A.1. A 100-years long ramp-up from a piControl run. The ramp-up considers +XGtC/yr as in TIPMIP-ESM (Jones et al., 2025 to reach 2 degrees of warming (+2C/century) in the non-hosed setup. Simultaneously, and as in TIPMIP-OCEAN experiments A (Swingedouw et al., 2026), the ramp-up also considers a freshwater flux along Antarctica that increases from 0 Sv at year 1 to 0.1 Sv at year 100. The location of the freshwater hosing follows the mask from the SOFIA initiative (Swart et al., 2023).

A.2. A 250-years long run with the forcing of 0.1 Sv of freshwater hosing and zero emissions. This is a branch off run from A.1, in which the emissions are set to zero to fix the Global Warming Level (GWL) at 2C, and a constant freshwater input continues.

A.3. A 100-years long ramp-down run from 50 years of stabilized 2C GWL. This run starts from year 50 of experiment A.2. The ramp down considers  $-XGtC/yr$  to reach the global temperature conditions of the pre-industrial ones. At the same time, the freshwater flux along Antarctica decreases from  $+0.1Sv$  to  $0 Sv$  at year 100.

A.4. A 150-years long run in which both forcings are turned off (emissions and freshwater flux are set to zero). This experiment is like a piControl experiment, but the initial condition is the final state of experiment A.3.

B. Dual freshwater hosing in the Southern Ocean and around Greenland within global warming (600 years)

B.1 A 100-years long ramp-up from a piControl run. The ramp-up considers  $+XGtC/yr$  to reach 2 degrees of warming ( $+2C/century$ ) in the non-hosed setup. The ramp-up also considers a freshwater flux along both, Greenland and Antarctica. For each ice-sheet, the freshwater hosing increases from  $0 Sv$  at year 1 to  $0.1 Sv$  at year 100. The locations of the freshwater hosing follow the mask from experiments A of TIPMIP-OCEAN in Greenland, and from SOFIA in Antarctica.

B.2. A 250-years long run with the forcing of  $0.1 Sv$  of freshwater hosing in both, Greenland and Antarctica, and zero emission. This run branches off from A.1, in which the emissions are set to zero to fix the Global Warming Level (GWL) at 2C, and a constant freshwater input continues.

B.3. A 100-years long ramp-down run from 50 years of stabilized 2C GWL. This run starts from year 50 of experiment B.2. The ramp down considers  $-XGtC/yr$  to reach the global temperature conditions of the pre-industrial ones. As the same time, the freshwater flux along Greenland and Antarctica decreases from  $+0.1Sv$  to  $0 Sv$  at year 100.

B.4. A 150-years long run in which both forcings are turned off (emissions and freshwater flux are set to zero). This experiment is like a piControl experiment, but the initial condition is the final state of experiment B.3.

### 3. Justification for the resources requested

Given the scientific urgency of producing coordinated simulations for the IPCC AR7, the proposed computational strategy is designed to ensure timely delivery of results while maintaining consistency with the TIPMIP-OCEAN and SOFIA projects.

The simulations will be executed in two phases: Experiments A during the first project year (2026) and Experiments B during the second project year (2027). Each experiment set consists of a 600-year coupled Earth System Model integration, resulting in a total of 1,200 simulated model years.

Based on previous production runs with EC-Earth3-ESM on the ATOS with an equivalent model configuration, the computational cost is estimated at approximately 40,000 SBU per model year. This cost includes full coupled atmosphere–ocean–sea ice–land–carbon cycle interactions at standard CMIP6 resolution. Consequently, each 600-year experiment requires approximately 24,000,000 SBU, resulting in a total computational demand for the full project of 48,000,000 SBU over two years.

With regards to the storage, considering the standard outputs following the TIPMIP-OCEAN data request for all the components of the Earth system model, including atmosphere, ocean, sea ice, land surface, and biogeochemistry, the requirement for the storage is around 80 GB of raw data per model-year. For the full set of simulations (1200 model years), this corresponds to a total amount of required space at the end of the project of around 96 TB. Storage resources will be split into equal parts between the two years of the project.

## References

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- Döscher, R., Acosta, M., Alessandri, A., et al. (2022). The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6. *Geoscientific Model Development*, 15, 2973–3020, <https://doi.org/10.5194/gmd-15-2973-2022>.
- Jones, C., Bossert, I., Dennis, D. P., et al. (2025). The TIPMIP Earth system model experiment protocol: phase 1, EGU sphere [preprint]. <https://doi.org/10.5194/egusphere-2025-3604>
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- Swart, N. C., Martin, T., Beadling, R., et al. (2023). The Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative: scientific objectives and experimental design, *Geosci. Model Dev.*, 16, 7289–7309, <https://doi.org/10.5194/gmd-16-7289-2023>.
- Swingedouw, D., Jackson, L., Hu, A., et al. (2026). TIPMIP-OCEAN experimental protocol phase 1: Tipping dynamics of the AMOC, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2026-1698>.
- Winkelmann, R., Dennis, D. P., Donges, J. F., et al. (2025). The Tipping Points Modelling Intercomparison Project (TIPMIP): Assessing tipping point risks in the Earth system, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2025-1899>.