

LATE REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: Italy

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Project Title: AMOC tipping and recoverability across Global Warming Levels in EC-Earth3

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 X	NO

Computer resources required for project year:	2026	2027	2028
High Performance Computing Facility [SBU]	39,550,000		
Accumulated data storage (total archive volume) ² [GB]	110,000		

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 Special 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.

³The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

Principal Investigator:

Giada Cerato

Project Title:

AMOC tipping and recoverability across Global Warming Levels in EC-Earth3

Extended abstract

The Atlantic Meridional Overturning Circulation (AMOC) is a complex system of surface and deep ocean currents which develops in the Atlantic basin, and forms a distinct but fundamental part of the global oceanic circulation. It is believed to cause an imbalance in the transport of heat between the hemispheres of ~ 0.5 PW (Trenberth et al., 2019), which makes the Northern Hemisphere around 1°C warmer than the Southern Hemisphere (Feulner et al., 2013, Buckley and Marshall 2016) and sets the latitude of the Intertropical Convergence Zone (ITCZ) to $\sim 5^\circ$ North of the Equator (Frierson et al., 2013; Marshall et al., 2014). The AMOC has been classified as one of the core tipping elements of the climate system (McKay et al., 2022), implying the existence of critical thresholds (e.g. global temperature or freshwater input at high latitudes) beyond which the circulation may transition to an alternative stable equilibrium.

The anthropogenic warming is believed to be a threatening factor for the AMOC stability by altering the density structure and stratification of the North Atlantic (Smeed et al. 2018). Despite a substantial AMOC weakening is consistently projected across CMIP6 models under global warming (Weijer et al. 2020; Bellomo et al. 2021), an actual tipping transition has rarely been observed in global simulations driven solely by increasing greenhouse gas concentrations (Romanou et al. 2023). In general, the AMOC bistability has not been detected in many global climate models (GCMs), rising the question whether it should be considered a monostable system or if the representation of the AMOC in GCMs is overly stable (Liu et al. 2014, Liu et al. 2016).

Despite the poor understanding of a possible abrupt transition to a weaker AMOC state, efforts have been done to understand impacts that a substantial AMOC weakening would have on the global climate system (Jackson et al. 2015; Liu et al. 2020; Bellomo et al. 2021). Such impacts are expected to include substantial regional and global climate responses, including Northern Hemisphere temperatures drop, changes in large-scale atmospheric circulation, and modifications of global precipitation patterns (Bellomo et al. 2023, Cerato et al. 2025, Vacca et al 2025). However, uncertainties in 21st-century climate change projections compound the uncertainty in both the timing and magnitude of AMOC weakening, thereby complicating the attribution of its impacts relative to those of global warming (Bellomo et al. 2021).

To separate the climatic effects of an AMOC collapse from other climate feedbacks, comprehensive GCMs have typically relied on strong freshwater perturbations to induce such transitions (e.g. Orihuela-Pinto et al., 2022). However, to the authors' knowledge, only one ad-hoc experiment has so far demonstrated an AMOC tipping as a response to internal feedbacks rather than from a strong external forcing (van Western et al. 2024). This result was obtained by applying a quasi-equilibrium freshwater perturbation in the Community Earth System Model (CESM), which employs the POP2 ocean model. Because POP2 differs substantially from other ocean models in its representation of deep convection, vertical mixing, and freshwater feedbacks (all processes that are critical for AMOC stability), this raises the question of whether a consistent AMOC tipping can occur in other state-of-the-art climate models employing different ocean models configurations and resolution.

In summary, current understanding points to several critical knowledge gaps. A growing body of literature suggests that the AMOC can abruptly transition to a weaker stable equilibrium in response to internal feedbacks, employing targeted experiments and global warming low-emission scenarios (Romanou et al. 2023, van Western et al. 2024). However, the associated early warning signals and the physical mechanisms governing such a collapse have so far been only partially investigated. Moreover, the potential for AMOC tipping under higher-emission scenarios remains largely unassessed.

Building on these knowledge gaps, this project investigates the potential for AMOC tipping across realistic global warming levels using targeted freshwater-forcing experiments with the EC-Earth3 model (Doescher et al. 2022) in its low resolution version, archived in the CMIP6. We will perform a suite of freshwater hosing experiments under progressively warmer background climate states, branched from quasi-equilibrated high-emissions (RCP8.5) simulations. In addition to inducing an AMOC weakening or collapse, we will explore the associated hysteresis behaviour for at least one of the two simulations.

The proposed experiments will enable us to:

(i) assess whether an AMOC tipping transition can occur in EC-Earth3 without an abrupt external forcing, and how its emergence and characteristics depend on the background ocean mean state (i.e. stratification and sea-ice conditions); (ii) identify and evaluate physically based early-warning signals preceding AMOC tipping under realistic levels of global warming; (iii) quantify the climatic impacts of an AMOC collapse or pronounced weakening across different background climate states (e.g. Bellomo and Mehling 2024); (iv) examine the reversibility of an abrupt AMOC transition and characterize the persistent climatic fingerprint of an AMOC transition after its state has returned to near-normal conditions.

2. Proposed activities

2.1 Model

We plan to perform a suite of model experiments using EC-Earth3-LR, a state-of-the-art global climate model developed by the EC-Earth Earth System Model (ESM) consortium and contributing to the CMIP6 (Coupled Model Intercomparison Project Phase 6). EC-Earth3 is a fully coupled Earth system model comprising the ECMWF Integrated Forecasting System (IFS) cycle 36r4 for the atmosphere, the NEMO v3.6 ocean model coupled with the LIM3 sea-ice component, the H-TESSSEL land surface scheme, and the OASIS3-MCT coupler.

The proposed simulations are conducted at the low CMIP6 resolution of EC-Earth3, featuring a spectral truncation of TL127 with 57 vertical levels in the atmosphere and an ORCA1 ocean grid with 75 vertical levels. EC-Earth3-LR is already installed and routinely used on the ECMWF ATOS high-performance computing system, ensuring full technical readiness for the proposed experiments.

2.2 Simulations

2.2.1 Quasi-equilibrium freshwater hosing

The proposed experiments build on previously conducted experiments under the special project SPITVACC. The simulations were initially branched from existing EC-Earth3 multi-centennial stabilization runs under different fixed levels of anthropogenic forcing (Fabiano et al. 2024). After a spinup period, two freshwater hosing experiments were initiated but never completed, following the protocol designed by Van Western et al. 2024.

In the present project, we aim to resume these previous hosing simulations and carry them through to completion. Specifically, the experiments adopt a quasi-equilibrium framework in which a virtual freshwater flux anomaly is applied in the North Atlantic region (as schematically illustrated in inset of Fig. 1). The freshwater forcing increases linearly at a rate of $0.0003 \text{ Sv yr}^{-1}$ (equivalent to $0.0003 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ per year) and is imposed between 20°N and 50°N . To conserve global salinity, the freshwater flux anomaly is compensated over the remainder of the ocean domain.

2.2.2 Full AMOC Hysteresis cycle

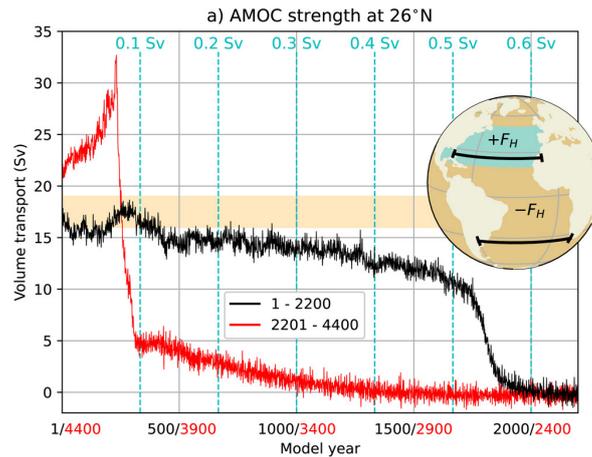


Figure 1. Schematic illustration of AMOC hysteresis behavior under idealized freshwater forcing, adapted from van Westen et al. (2023). (a) AMOC strength at 1,000 m depth and 26°N. Cyan vertical lines indicate the magnitude of the imposed freshwater forcing F_H , while yellow shading denotes the observed range of the corresponding quantity. Inset: Freshwater is added at the ocean surface between 20°N and 50°N in the Atlantic Ocean (+ F_H) and compensated over the remaining ocean surface (- F_H) to conserve global salinity.

Since at least one of the two simulations exhibits potential tipping behaviour, as indicated by a departure from linearity in the AMOC decline rate after approximately 900 model years (although the transition itself had not yet been reached in SPITVACC, as explained in Section 2.2.1), we plan to perform a full hysteresis cycle for this simulation in order to assess whether the observed behaviour is indeed indicative of AMOC tipping, following the experiments introduced by Van Westen et al. 2023 (see Fig.1). Once the AMOC will have reached a weakened equilibrium state, we will initialize a branched experiment in which the freshwater forcing is reversed, building the recovery branch of the AMOC hysteresis diagram.

We further plan to perform a couple of additional equilibrium experiment following van Westen et al. (2025), one from each branch of the AMOC hysteresis cycle (~600 years each). By minimizing long-term drift, these simulations ensure that the AMOC and associated climate variability are dominated by internal variability, enabling a robust comparison between the two equilibrium states.

3. Justification of the computer resources

Based on the simulations previously conducted within the SPITVACC project on ECMWF ATOS, the computational cost is estimated at approximately 7000 SBU per simulated year. Also, the output from one simulated year is stored in ~27 GB per year. The following Table summarizes the planned experiments, the corresponding number of simulated model years expected for their completion, the associated SBU demand and expected total storage needed.

Experiment	Model years	Expected SBU usage	Storage
Quasi equilibrium hosing 2025 warming level	700 + 200	6,300,000	24.3 T
Quasi equilibrium hosing 2080 warming level	1150 + 200	9,450,000	36.5 T
Hysteresis of 2025 hosing	2200	15,400,000	59.4 T
Statistical equilibrium	1200	8,400,000	32.4 T

The 2025 simulation has currently progressed for 1223 model years. Based on the present weakening rate of approximately -1 Sv per century, we estimate that an additional ~700 model years are required for the AMOC to reach ~3 Sv, followed by ~200 years for stabilization.

The 2080 simulation has so far advanced for 122 model years and exhibits a nearly linear weakening rate of about -0.5 Sv per century. At this rate, we estimate that $\sim 1,300$ additional model years are needed to reach ~ 3 Sv, followed by ~ 200 years for stabilization.

For the hysteresis experiment, we assume a comparable integration length to that of the corresponding tipping experiment. Taken together, the total number of simulated years required is therefore estimated to be approximately 2200 model years.

Total of 39,550,000 SBU requested.

The total computational cost amounts to 39,550,000 SBUs. The total estimated storage requirement is approximately 152 TB. However, for the hysteresis experiments we plan to save a reduced set of model output. As a result, the effective storage request is reduced to approximately 110 TB.

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