EMI R&D 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	2026
Project Title:	Sampling AMOC tipping events with a rare event algorithm with a low resolution version of state of the art model
Computer Project Account:	spitcini
Principal Investigator(s):	Matteo Cini
Affiliation:	Università degli Studi di Torino, ISAC-CNR
Name of ECMWF scientist(s) collaborating to the project (if applicable)	…………………………………………………………… ……………………………………………………………
Start date of the project:	1/01/2025
Expected end date:	31/12/2026

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)	23.500.000	**16,027,060**	16,500,000	**16,282,197**
Data storage capacity	(Gbytes)	55,000		80,000	**1,801**

Summary of project objectives (10 lines max)

This project investigates the collapse of the Atlantic Meridional Overturning Circulation (AMOC) using a hierarchy of climate models that ranges from in large-ensemble simulations in an intermediate-complexity model (PlaSim coupled to LSG, T21 resolution) to a single deterministic simulation with a state-of-the-art Earth System Model (EC-Earth). The simulations with the lower-complexity model specifically address the growing evidence for stochastic AMOC collapses and aim to quantify the probability of such collapses (Mehling et al., 2023; Romanou et al., 2023; Cini et al., 2024). Because estimating this probability accurately through large-ensemble simulations is computationally very expensive, we apply rare-event techniques to sample these events efficiently and thereby improve the accuracy of the estimate. A second part of the project examines AMOC stability within the Tipping Points Modelling Intercomparison Project (TIPMIP; Winkelmann et al., 2025), and in particular its ocean component, TIPMIP-OCEAN (Swingedouw et al., 2026).

Summary of problems encountered (10 lines max)

No major problems were encountered during last year.

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

Concerning the probabilistic assessment of AMOC collapses, we have so far successfully performed ensemble simulations of 256 trajectories with the Trajectory-Adaptive Multilevel Splitting (TAMS) algorithm using PlaSim-LSG (see Summary of results). The allocated computational resources are now almost exhausted, so we do not expect to obtain further results along this line of the project within the current allocation. In the future, additional resources may be requested in order to apply the same technique to higher-complexity models.

Concerning the deterministic TIPMIP-OCEAN simulations, the analysis of the completed experiments is still ongoing and will be finalised for publication.

List of publications/reports from the project with complete references

- **Cini et al. (2026)** : the paper presenting the TAMS algorithm and the associated PlaSim-LSG simulations has recently been published (full reference below).
- **Swingedouw et al. (2026, preprint)** : it includes the simulations related to the deterministic part of this project (full reference below).

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.

Part 1. Probabilistic assessment of AMOC collapse

The results of the first part of the project, the assessment of AMOC collapse probability, are presented in Cini et al. (2026), and the main achievements are summarised here. Thanks to the computational resources provided, we successfully applied the Trajectory-Adaptive Multilevel Splitting (TAMS) algorithm to several large-ensemble simulations (256 members) with the intermediate-complexity climate model PlaSim-LSG. TAMS is a discarding-and-cloning algorithm that operates on ensemble simulations to progressively populate a desired target state. Here it was used to populate an AMOC ensemble with low-AMOC states (AMOC index below 9.4 Sv). The resulting ensemble constitutes a realistic ensemble simulation consistent with the model physics (no external driving mechanism is imposed) associated with a probability derived from the number of discarded trajectories.

We conducted two main types of simulations:

1 **Equilibrium simulations** at constant CO_2 concentrations (500 ppm and 600 ppm), run over 150 years. These indicate that the probability of an AMOC collapse is significantly different from zero over the 150-year period, with a magnitude that depends on the CO_2 level.
2 **Scenario-based simulations** following SSP emission trajectories up to the year 2200. These suggest that, while an AMOC collapse is unlikely during the 21st century, it becomes increasingly probable by 2150 under high-emission scenarios, and is almost certain by 2200 under SSP5-8.5.

It is important to note that PlaSim-LSG does not include the freshwater flux associated with Greenland meltwater. Because this flux tends to weaken the AMOC, its omission biases the model towards a more stable AMOC-on state; including it would therefore likely increase the estimated collapse probabilities. Overall, these findings highlight the value of probabilistic approaches and rare-event sampling algorithms for assessing AMOC stability and understanding its tipping dynamics.

Part 2. Deterministic simulations for TIPMIP-OCEAN

Regarding the second part of the project, the deterministic simulations carried out within TIPMIP, the analysis of the results is still ongoing. Preliminary results have already been included in the preprint by Swingedouw et al. (2026). Note that only part of those simulations were performed in the context of this project. We briefly introduce below the simulations for which computational resources has been used in this project.

Idealised freshwater-hosing experiments and CO2 scenarios are used to examine AMOC stability in state-of-the-art climate models. In these experiments, an artificial freshwater input is added to the North Atlantic to represent the effect of Greenland melting. This tends to suppress deep-water formation, causing the AMOC to weaken and potentially collapse.

TIPMIP-OCEAN Experiment A tests the sensitivity of the North Atlantic to global warming driven by increased CO_2 emissions, combined with an additional freshwater input that increases and decreases in phase with the CO_2 forcing. Experiment A comprises four phases, analogous to the non-hosed TIPMIP-ESM experiment:

1 A CO_2 ramp-up branches from a pre-industrial simulation and runs for approximately 100 years at +X GtC/yr, using the same emission rate X as the TIPMIP-ESM protocol (Jones et al., 2026). The novelty here is the addition of a prescribed freshwater flux that increases from 0 Sv in year 1 to +0.3 Sv (or +0.1 Sv) by year ~100—the same year at which the global-warming stabilisation run begins in TIPMIP-ESM.

2 A zero-emission run branches off phase (1) when GMSAT reaches 2 °C in TIPMIP-ESM (and Y °C in the hosed ramp-up experiments, potentially different because of interactions with the hosing). It starts in the same year chosen to begin the stabilisation run in TIPMIP-ESM, also retains the +0.3 Sv (or +0.1 Sv) freshwater flux, and runs for 250 years.

3 After 50 years of phase (2), emissions are set to −X GtC/yr to ramp down towards pre-industrial conditions; this phase starts with the +0.3 Sv (or +0.1 Sv) freshwater flux, which then decreases back to 0 Sv over about 100 years.

4 At around year 100 of phase (3)—when the 31-year-averaged GMSAT returns to its pre-industrial value in TIPMIP-ESM—both emissions and the freshwater flux are set to zero, and the run is extended for a further 100 years under external forcings equivalent to a pre-industrial run.

Experiment C, by contrast, applies freshwater hosing in the North Atlantic and Arctic for 50 years, followed by removal of the forcing and a 100-year recovery period during which the model evolves freely. We performed four 150-year simulations with EC-Earth3-ESM, using freshwater forcings of 0.3 Sv (standard protocol) and 3.0 Sv under two background climate states. Consistent with previous NAHosMIP results (Jackson et al., 2023), the AMOC recovers after the 0.3 Sv perturbation is removed, under both pre-industrial and +2 °C conditions, indicating strong resilience. In contrast, the 3.0 Sv forcing triggers a complete AMOC collapse that persists after the hosing ceases, with no recovery during the post-forcing period (Figure 1).

Figure 1: Time series of the AMOC index at 26°N for the Experiment C simulations performed with EC-Earth3-ESM as a contribution to TIPMIP-OCEAN. Shown are the experiments with freshwater-hosing strengths of 0.3 Sv (blue) and 3.0 Sv (green), together with the background climates (grey). Dashed lines denote the pre-industrial background climate and solid lines the +2 °C (2 GWL) background climate.

References

- Mehling, O., Börner, R., & Lucarini, V. (2023). Limits to predictability of the asymptotic state of the Atlantic Meridional Overturning Circulation in a conceptual climate model. *Physica D: Nonlinear Phenomena*, 459, 134043. https://doi.org/10.1016/j.physd.2023.134043
- Romanou, A., Rind, D., Jonas, J., Miller, R., Kelley, M., Russell, G., Orbe, C., Nazarenko, L., Latto, R., & Schmidt, G. A. (2023). Stochastic bifurcation of the North Atlantic circulation under a midrange future climate scenario with the NASA-GISS ModelE. *Journal of Climate*, 36(18). https://doi.org/10.1175/JCLI-D-22-0536.1
- Cini, M., Zappa, G., Ragone, F., & Corti, S. (2024). Simulating AMOC tipping driven by internal climate variability with a rare event algorithm. *npj Climate and Atmospheric Science*, 7(1), 1–10. https://doi.org/10.1038/s41612-024-00568-7
- Cini, M., Dijkstra, H. A., Jacques-Dumas, V., & Zappa, G. (2026). Assessing the probability of CO_2-driven AMOC transitions using a rare event algorithm in PlaSim-LSG. *Journal of Physics: Complexity*, 7, 02LT02.
- 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. *EGUsphere* [preprint]. https://doi.org/10.5194/egusphere-2025-1899
- Swingedouw, D., Jackson, L., Hu, A., et al. (2026). TIPMIP-OCEAN experimental protocol phase 1: Tipping dynamics of the AMOC. *EGUsphere* [preprint]. https://doi.org/10.5194/egusphere-2026-1698
- Jackson, L. C., Alastrué de Asenjo, E., Bellomo, K., et al. (2023). Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project. *Geoscientific Model Development*, 16, 1975–1995. https://doi.org/10.5194/gmd-16-1975-2023

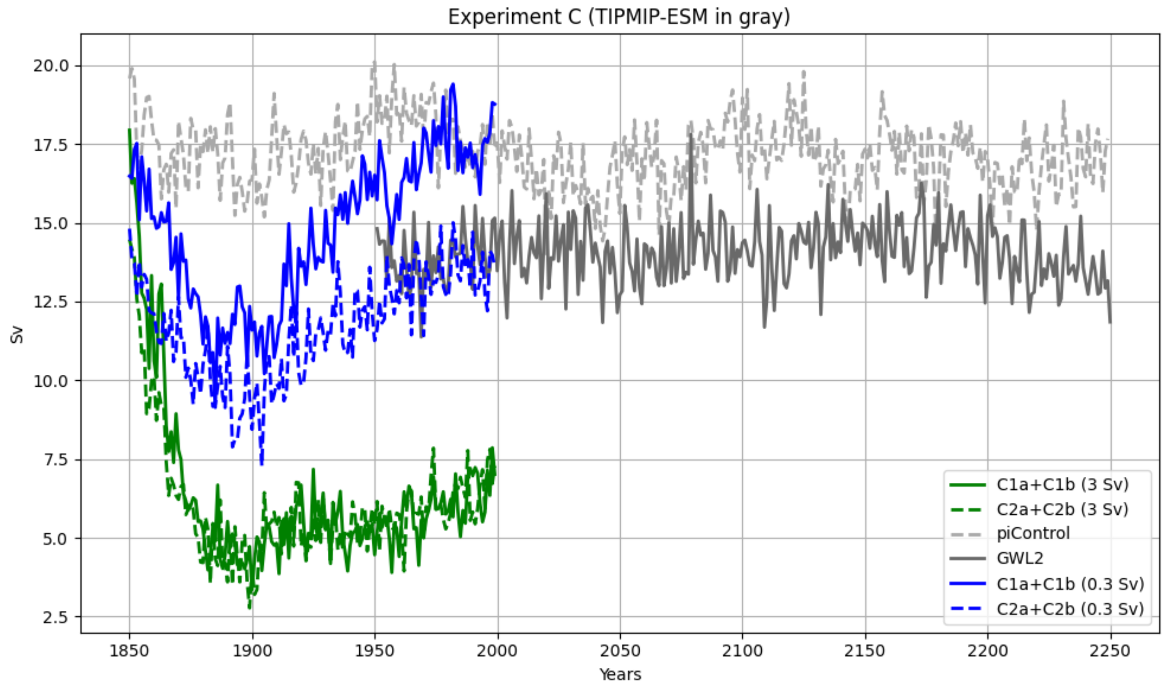

Figure 1: Timeseries of the AMOC index at 26N for the Experiments C performed with EC-Earth3-ESM to participate in TIPMIP-OCEAN. Experiments with freshwater hosing strength of 0.3 Sv (in blue) and 3.0 Sv (in green), and the background climates (in gray) are displayed. Dashed lines are the experiments with pre-industrial background climate and solid lines with 2 GWL background climate.