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:	…… Limaloc: long-term impact of meltwater from antarctica on large-scale oceanic circulations ……………………………………………….……
Computer Project Account:	……………spittro2…………………………..……
Principal Investigator(s):	…………Irene Trombini …… …………………………………………………………..……
Affiliation:	University of Bologna, CNR-ISAC
Name of ECMWF scientist(s) collaborating to the project (if applicable)	CNR-ISAC: Valerio Lembo, Susanna Corti KNMI: Eveline van der Linden, Luna Hiron, Erwin Lambert SMHI: Dorothée Vallot
Start date of the project:	……………1.01.2025
Expected end date:	……………31.12.2027….……

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)	7 750 000	9 000 000	11 000 000	1 500 000
Data storage capacity	(Gbytes)		0		12 000

Summary of project objectives (10 lines max)

The LIMALOC project aims to investigate the long-term impact of Antarctic meltwater on large-scale oceanic circulations, such as the Antarctic Circumpolar Current (ACC) and the Atlantic Meridional Overturning Circulation (AMOC). Using the EC-Earth family of climate models, the project aims at comparing prescribed meltwater forcing (hosing experiments) with simulations where meltwater is computed interactively using an emulator. It explores how two-way coupling affects meltwater fluxes and their climatic consequences under different warming scenarios. The project also aims to finalise EC-Earth's contribution to the SOFIAMIP experiment suite and make the hosing code available for EC-Earth to contribute to other multi-model comparison projects. Ultimately, LIMALOC aims to understand how meltwater from ice sheets could influence future ocean characteristics and circulation patterns under climate change.

Summary of problems encountered (10 lines max)

Migration from EC-Earth3 to EC-Earth4: As the EC-Earth family transitions from the CMIP6 version to the new generation for CMIP7, we decided to contribute to EC-Earth4's development by porting and improving the Antarctic Ice Melt Emulator (AIME), rather than sustaining the legacy EC-Earth3 setup. This decision was mainly driven by the fact that in ECE4 the antarctic cavities are open, in contrast to ECE3, and this is key for ice-ocean interactions. This decision involved delaying certain runs for the original scope of the LIMALOC project but enables a more realistic representation of the Southern Ocean, with the following benefits: (1) CMIP7 Fast Track runs with EC-Earth4 will include meltwater fluxes, a major improvement over CMIP6 that is key for Southern Ocean processes and carries potential global climate impacts under strong warming scenarios, according to recent work by van der Linden et al. (in prep). The new runs produced within LIMALOC, and the deriving scientific work, will benefit of the improvede representation.

SOFIAMIP Tier2: numerical instability when large prescribed freshwater fluxes are combined with extreme warming scenarios. This is being addressed by increasing hosing depth.

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

Work planned for the rest of the current project year and for 2027 will focus on

- development: refinement of the 5 regions in which the calving is applied using maps derived from coupled simulations with Lagrangian icebergs. This aims at avoiding unrealistic sharp gradients that can arise in the current configuration (Figure 1c).

- production runs

- analysis of the sensitivity of the tipping of the cavities and of the broader Southern Ocean climate response to warming and freshwater fluxes. To isolate the role of these latter, simulations using a high and low sensitivity emulator configurations will be compared. In addition, to isolate the contribution of meltwater fluxes, simulations with and without AIME will be examined.

List of publications/reports from the project with complete references

- Recent technical developments regarding AIME in EC-Earth4 were presented at the EC-Earth General assembly (Barcelona, 9-12 June 2026) as part of the work of the Land Ice Working Group, and are currently being summarized in the technical description paper of EC-Earth4, planned for submission in January 2027. AIME is briefly described in the official EC-Earth4 documentation https://ec-earth-4-docs.readthedocs.io/en/latest/running/main.html#aime-antarctic-ice-melt-emulator
- Involvement in the definition of the protocol for the TIPMIP-OCEAN Phase 1 Modeling Intercomparison Project, leading to the co-authorship of the manuscript by Swingedouw et al. (2026), currently under review in Geoscientific Model Development.
- Contribution of SOFIA experiments with EC-Earth3 to water mass transformation analysis for the EU Horizon Project OCEAN:ICE, manuscript led by BAS, currently in prep.

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: Porting and improvement of the Antarctic Ice Melt Emulator (AIME)

The work carried out within the LIMALOC project from its start focused on improvement and porting of the Antarctic Ice Melt Emulator (AIME) to the main version of EC-Earth4, that will be used for the CMIP7 Fast Track simulations, in collaboration with researchers at KNMI (Eveline van der Linden, Luna Hiron, Erwin Lambert) and SMHI (Dorotheé Vallot).

The AIME represents freshwater fluxes from the melting of the Antarctic ice sheet in response to ocean thermal forcing. In CMIP6-class climate models, such as EC-Earth3 (Doescher et al., 2022), the Antarctic ice sheet does not evolve dynamically, and freshwater fluxes from Antarctica were simply coming from precipitation over the continent being redirected to the ocean once a threshold was surpassed (excess-snowfall). In contrast, the EC-Earth-AIME setup includes a first-order response of the ice sheet to increasing ocean temperatures in terms of meltwater fluxes. As in our implementation ocean these latter, in turn, affect ocean temperatures, first-order ice-ocean feedbacks are captured.

AIME is based on linear response functions (LRFs) derived from stand-alone ice sheet model simulations, adapting the LARMIP-2 setup (Levermann et al. 2020) as described in detail in (Lambert et al. 2025). The linear response functions are calculated for five sub-regions of the Antarctic Ice Sheet, displayed in Figure 1a, following (Levermann et al. 2020). The emulator is a lightweight Python tool that avoids full coupling to a dynamical ice sheet model. It computes meltwater fluxes per subregion using two inputs: ice LRFs computed offline for a given ice sheet model, and yearly mean basal melt anomalies, the latter derived from ocean temperatures via the quadratic parametrization (Favier et al. 2019). For each model year, the meltwater fluxes are then imposed as new boundary conditions to the ocean model NEMO and act on the ocean temperature, thereby introducing a feedback on the meltwater flux. In EC-Earth meltwater fluxes are implemented both as iceberg calving, inserted at the ocean surface, and as basal melting, with freshwater inserted at depth. Both fluxes remove latent heat of fusion from the ocean.

In addition to technical work — such as implementing both coupled and stand-alone options for AIME within the EC-Earth4 script-engine framework — this project contributed to several improvements over the previous AIME version included in EC-Earth3-ESM, basing on previous work by van der Linden et al, in prep. These are:

1. Ocean to ice

    a) Ice shelf cavities: use of ocean temperatures in Antarctic ice shelf cavities instead of on the continental shelf for the thermal forcing. The ocean sectors used for the thermal forcing, displayed in Figure 1b, are defined by adapting the ocean sectors in Levermann et al., (2020).

    b) Use of updated basal melt sensitivities. These are computed using the parametrizations of ice-ocean interactions of the LADDIE model (Lambert et al. 2026).

    c) Implementation of the dependence of freezing temperature (Tf) on ocean salinity and pressure using the latest TEOS formulation as it is implemented in the gsw python package (https://teos-10.github.io/GSW-Python/). While in the previous implementation of the AIME the freezing temperature was set to be constant in time and space to 1.9°C, we introduce now a formulation allowing Tf to change with simulated ocean salinity and pressure. This has resulted in a larger sensitivity of the freshwater fluxes to ocean temperatures, as shown in Figure 2 for a test experiment.

2. Ice to ocean

   a) Regional redistribution of freshwater fluxes. Whereas in ECEarth3-ESM the meltwater anomalies were redistributed uniformly over the Southern Ocean, in ECE4 we apply the meltwater to the corresponding ocean region that was used to calculate the anomaly. Basal melt is injected in the top layer of the ice shelf cavities (at depths ranging between ~1000 m and ~200 m), whereas for calving we apply the freshwater at the surface following the regions displayed in Figure 1c (adapting ocean sectors that defined in Levermann et al., 2020). We apply both basal melt and iceberg melt making use of spatial patterns derived from non-AIME simulations with the NEMO formulations for the three-equations and Lagrangian icebergs, respectively. In addition, we account for iceberg drift by introducing a simplified iceberg rerouting based on previous work by Lambert et al., (2025) and van der Linden et al, in prep.

   b) Improvement of the seasonality of meltwater fluxes. In ECEarth3-ESM the seasonality of excess snowfall, following the seasonality of precipitation-evaporation on the Antarctic continent, was used. We now use seasonalities retrieved from non-AIME ECEarth4 simulations described above, that are therefore consistent with ocean processes.

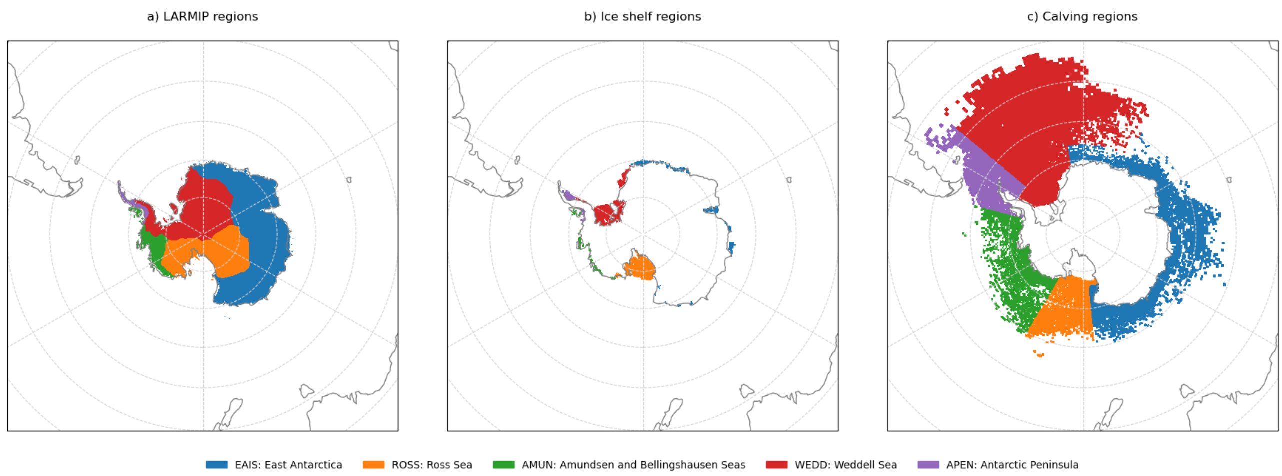

Figure 1: The five ice-sheet and ocean sectors used in this study and adapted from Levermann et al 2020. a) Regions used to compute the ice linear response functions, b) separation of ice shelf cavities into five regions used to both compute thermal forcing, and to subdivide the ice-shelf basal melt pattern to apply the respective fluxes. c) separation of the iceberg pattern into the five regions where freshwater flux from iceberg calving is applied.

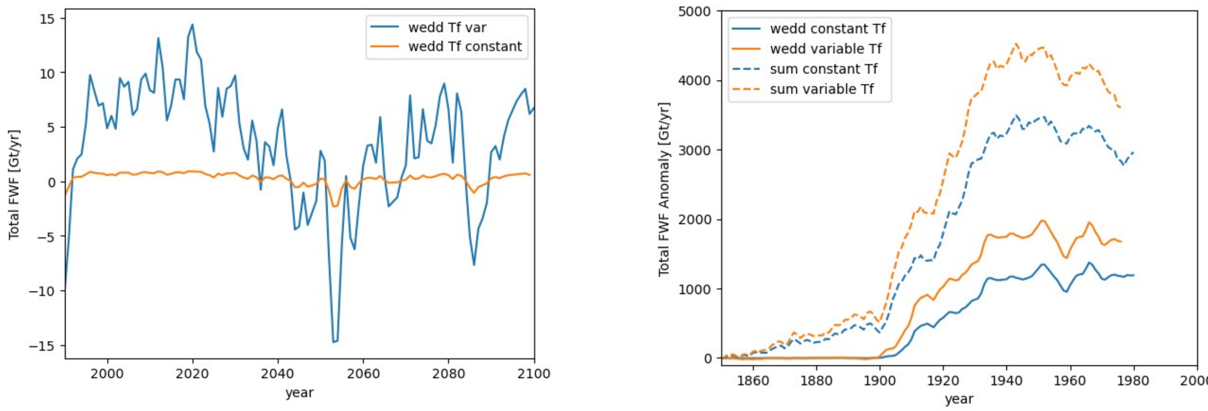

Figure 2: Sensitivity of the total freshwater anomalies (calving+basal melt) to different implementations of the freezing temperature (Tf) in the AIME. Meltwater from the Weddel region computed with standalone AIME forced by ocean temperatures of a non-AIME (left) piControl experiment (right) 4xCO2 test experiment. In the right panel the sum of total freshwater anomalies over the five regions is shown with dashed lines. The comparison between constant and variable Tf shows that including variable freezing temperature increases both the internal variability and the response to global warming of large ice shelves.

A first test simulation using EC-Earth4 was performed for the 4xCO2 standard experiment and is discussed in the following. The simulation was performed with the AOGCM+AIME configuration basing on EC-Earth4.1.6, with the aim of assessing the sensitivity of the model and ensure its stability under strong CO2 and freshwater forcing. For AIME we used ice LRFs from UFEMISM (Berends et al. 2025) in version 0.0.2.

Figure 3 shows the potential temperatures of the Antarctic continental shelf across the five ocean sectors defined above, enabling comparison of temperature changes within and outside the cavities. The simulation shows an abrupt shift from the cold to the warm mode (according to the classification by Jacobs et al. 1992) for both the two largest cavities, i.e. the ones of the Ross and Filchner-Ronne (FRIS) ice shelves. The nonlinear behaviour of the temperature in the ice shelf cavities is reflected in the meltwater fluxes shown in Figure 4. This presents a major difference with respect to the previous setup. In the ECE3-ESM implementation, AIME used the temperatures of the shelf, that are more linear. Using this setup, previous work from van der Linden et al, in prep, had found a strong and fast meltwater response to the abrupt greenhouse forcing. With the new implementation, on the contrary, the meltwater exhibits a delayed response, with a dramatic increase only after about 65 years of simulation, dominated by melt in the two largest ice shelves. Such "tipping" behaviour aligns with conceptual studies (e.g. Saddier et al. 2026). For FRIS, it is in agreement also with the most recent literature on the response of the FRIS cavity to strong warming using complex ocean (e.g. Hellmer et al. 2012, Mathiot and Jourdain 2023), coupled ice-ocean (e.g. Naughten et al. 2021) and Earth system models both with (Siahaan et al. 2022) and without interactive ice sheets (Song et al. 2025). Conversely, a regime shift of the Ross Ice Shelf cavity — though less abrupt — has been identified in only a subset of studies using complex numerical models (Mathiot and Jourdain 2023, Siahaan et al. 2022, Song et al. 2025). The emergence of this behaviour in the EC-Earth4-AIME configuration demonstrates that the new setup is an effective tool for investigating the sensitivity of both major cavities within our coupled system.

In conclusion, during the first phase of the project we ere able to demonstrate that these improvements enable more realistic first-order ice-ocean interactions, enhancing the representation of freshwater fluxes in the Southern Ocean under warming scenarios. Beyond advancing the model setup for CMIP7 production runs, this work establishes the foundation for subsequent research—specifically, examining the role of freshwater fluxes in driving the response of major Antarctic ice shelf cavities and the broader Southern Ocean to global warming.

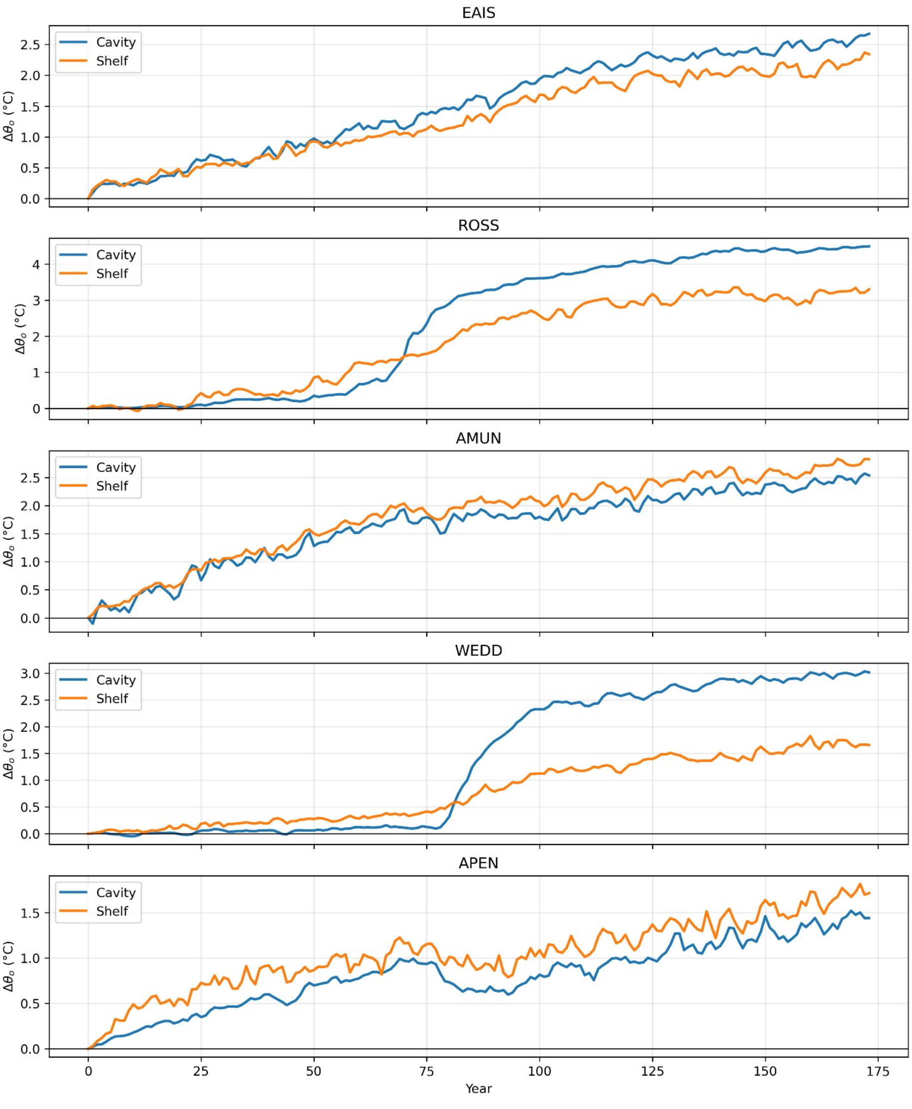

Figure 3: Timeseries of anomalies of ocean potential temperature with respect to simulation start for a 4xCO2 experiment with active AIME. Temperatures within antarctic cavities are shown in blue, over the Antarctic continental shelf excluding the cavities in orange. Credit: Eveline van der Linden.

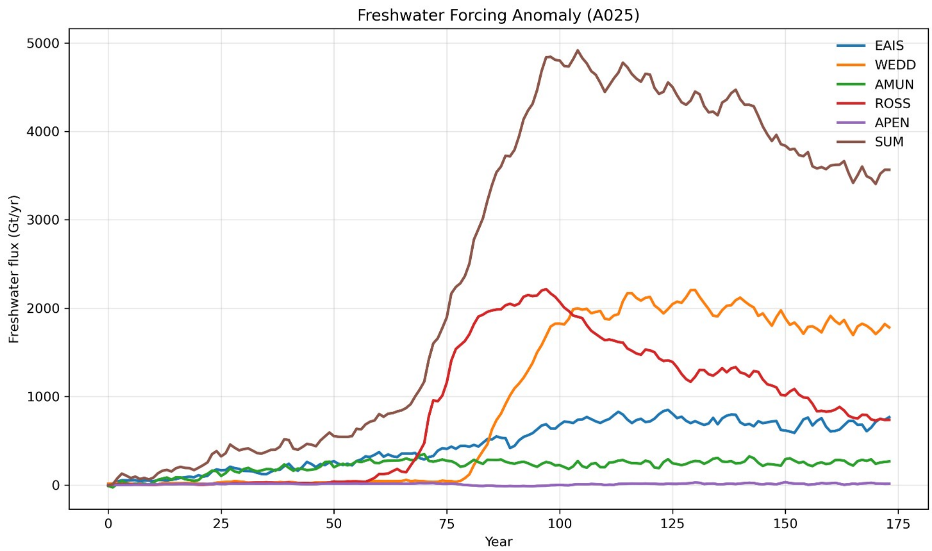

Figure 4: Timeseries of total freshwater fluxes (basal melt + calving) for a 4xCO2 experiment with AIME. When the largest ice shelves flip to a warm state, their meltwater contribution increases nonlinearly. Credit: Eveline van der Linden.

Part 2: EC-Earth3 contributions to SOFIA and TIPMIP-OCEAN Experiments

Idealised freshwater hosing experiments have been used to examine the stability of buoyancy-driven circualitons in state-of-the-art climate models. In such experiments, artificial freshwater inputs are introduced, for example into the North Atlantic and, as a result, deep-water formation tends to cease and the AMOC weakens or potentially collapses. Similar experiments have been carried out in the Southern Ocean, with the SOFIA Initiative (Swart et al. 2023) coordinating multimodel comparison efforts. In this project we contributed to both the SOFIA initiative and TIPMIP-OCEAN (Swingedouw et al. 2026) , by adapting the hosing code for this latter, testing the setup and performing simulations. Preliminary results from EC-Earth3-ESM TIPMIP-OCEAN simulations are described below.

Within the Tipping Points Modelling Intercomparison Project (TIPMIP; Winkelmann et al., 2025), the ocean component TIPMIP-OCEAN investigates AMOC stability under freshwater hosing in both pre-industrial and +2°C global warming level (GWL) background climates. Experiment C consists of applying freshwater hosing in the North Atlantic and Arctic for 50 years followed by the removal of the forcing and a 100-year recovery period during which the model evolves freely. We performed four 150-year simulations with the EC-Earth3-ESM (Figure 1) using freshwater forcing of 0.3 Sv (standard protocol) and 3.0 Sv under both climate states. Note that only part of these simulations were performed in the context of this project.

The AMOC recovers after the 0.3 Sv perturbation is removed, under both pre-industrial and +2 °C conditions, indicating strong resilience, consistent with previous results with EC-Earth3 (Guo et al.

2026, Mehling et al. 2026)) and multi-model studies (NAHosMIP, Jackson et al. 2023) . In contrast, the 3.0 Sv forcing triggers an AMOC collapse that persists after the hosing ceases, with no recovery during the post-forcing period (Figure 4). Analysis of the results is ongoing, and will focus both on the mechanisms behind AMOC weakening or collapse and the impacts on atmospheric circulation patterns, with a focus on the state dependency of the response. In addition, the ECEarth3-ESM data will be made available to the wider community on an ESGF node and will contribute to a multi-model study to inform IPCC AR7.

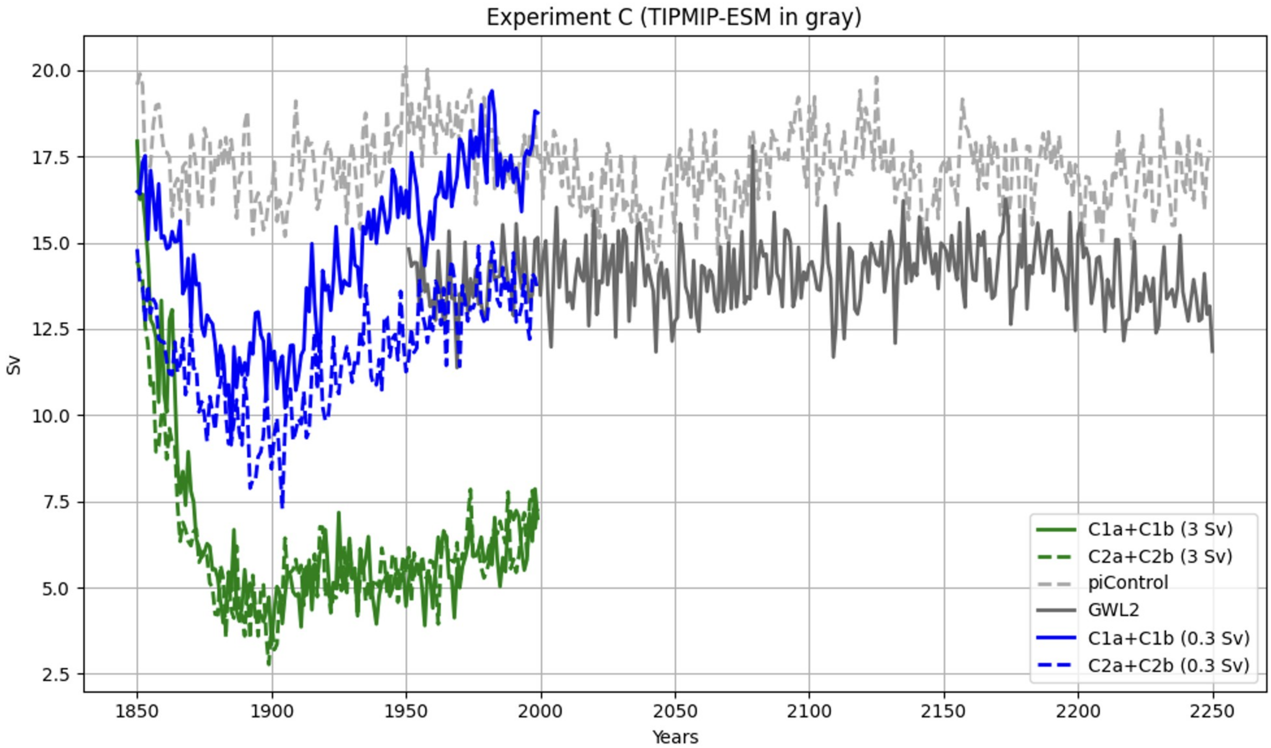

Figure 4: *Timeseries of the AMOC index at 26N for the Experiments C performed with EC-Earth3-ESM to participate in TIPMIP-OCEAN. Experiments with freshwater hosing strength of 0.3 Sv (in blue) and 3.0 Sv (in green), and the background climates (in grey) are displayed. Dashed lines are the experiments with pre-industrial background climate and solid lines with 2 GWL background climate. Credit: Virna Meccia.*

References

Berends, Constantijn J., Victor Azizi, Jorge A. Bernales, and Roderik S. W. van de Wal. 2025. "The Utrecht Finite Volume Ice-Sheet Model (UFEMISM) Version 2.0 – Part 1: Description and Idealised Experiments." *Geoscientific Model Development* 18 (12): 3635–59. https://doi.org/10.5194/gmd-18-3635-2025.

Favier, Lionel, Nicolas C. Jourdain, Adrian Jenkins, et al. 2019. "Assessment of Sub-Shelf Melting Parameterisations Using the Ocean–Ice-Sheet Coupled Model

NEMO(v3.6)–Elmer/Ice(v8.3).” *Geoscientific Model Development* 12 (6): 2255–83. https://doi.org/10.5194/gmd-12-2255-2019.

Guo, Chuncheng, Shuting Yang, Ilana Schiller-Weiss, et al. 2026. “Reversible Atlantic Overturning despite Continued Greenland Ice Sheet Melt.” Preprint, Research Square, February 5. https://doi.org/10.21203/rs.3.rs-7830432/v2.

Hellmer, Hartmut H., Frank Kauker, Ralph Timmermann, Jürgen Determann, and Jamie Rae. 2012. “Twenty-First-Century Warming of a Large Antarctic Ice-Shelf Cavity by a Redirected Coastal Current.” *Nature* 485 (7397): 225–28. https://doi.org/10.1038/nature11064.

Jackson, Laura C., Eduardo Alastrué de Asenjo, Katinka Bellomo, et al. 2023. “Understanding AMOC Stability: The North Atlantic Hosing Model Intercomparison Project.” *Geoscientific Model Development* 16 (7): 1975–95. https://doi.org/10.5194/gmd-16-1975-2023.

Jacobs, S. S., H. H. Helmer, C. S. M. Doake, A. Jenkins, and R. M. Frolich. 1992. “Melting of Ice Shelves and the Mass Balance of Antarctica.” *Journal of Glaciology* 38 (130): 375–87. https://doi.org/10.3189/S0022143000002252.

Lambert, Erwin, Franka Jesse, and Constantijn J. Berends. 2026. “The One-Layer Antarctic Model for Dynamical Downscaling of Ice–Ocean Exchanges (LADDIE) Version 2.0.” *EGUsphere*, April 23, 1–31. https://doi.org/10.5194/egusphere-2026-930.

Lambert, Erwin, Dewi Le Bars, Eveline van der Linden, André Jüling, and Sybren Drijfhout. 2025. “Quantifying the Feedback between Antarctic Meltwater Release and Subsurface Southern Ocean Warming.” *Earth System Dynamics* 16 (4): 1303–23. https://doi.org/10.5194/esd-16-1303-2025.

Levermann, Anders, Ricarda Winkelmann, Torsten Albrecht, et al. 2020. “Projecting Antarctica’s Contribution to Future Sea Level Rise from Basal Ice Shelf Melt Using Linear Response Functions of 16 Ice Sheet Models (LARMIP-2).” *Earth System Dynamics* 11 (1): 35–76. https://doi.org/10.5194/esd-11-35-2020.

Mathiot, Pierre, and Nicolas C. Jourdain. 2023. “Southern Ocean Warming and Antarctic Ice Shelf Melting in Conditions Plausible by Late 23rd Century in a High-End Scenario.” *Ocean Science* 19 (6): 1595–615. https://doi.org/10.5194/os-19-1595-2023.

Mehling, Oliver, Katinka Bellomo, Federico Fabiano, et al. 2026. “Limited Impact of Greenland Meltwater on Abruptness and Reversibility of Future Atlantic Overturning Changes.” *Science Advances* 12 (25): eaed2633. https://doi.org/10.1126/sciadv.aed2633.

Naughten, Kaitlin A., Jan De Rydt, Sebastian H. R. Rosier, Adrian Jenkins, Paul R. Holland, and Jeff K. Ridley. 2021. “Two-Timescale Response of a Large Antarctic Ice Shelf to Climate Change.” *Nature Communications* 12 (1): 1991. https://doi.org/10.1038/s41467-021-22259-0.

Saddier, Louis, Corentin Herbert, Christopher Y. S. Bull, and Louis-Alexandre Couston. 2026. “Irreversible Transitions of the Ocean Circulation in Antarctic Ice-Shelf Cavities.” *Geophysical Research Letters* 53 (4): e2025GL118278. https://doi.org/10.1029/2025GL118278.

Siahaan, Antony, Robin S. Smith, Paul R. Holland, et al. 2022. “The Antarctic Contribution to 21st-Century Sea-Level Rise Predicted by the UK Earth System Model with an Interactive Ice Sheet.” *The Cryosphere* 16 (10): 4053–86. https://doi.org/10.5194/tc-16-4053-2022.

Song, Pengyang, Patrick Scholz, Gregor Knorr, Dmitry Sidorenko, Ralph Timmermann, and Gerrit Lohmann. 2025. “Regional Conditions Determine Thresholds of Accelerated Antarctic Basal Melt in Climate Projection.” *Nature Climate Change* 15 (5): 521–27. https://doi.org/10.1038/s41558-025-02306-0.

Swart, Neil C., Torge Martin, Rebecca Beadling, et al. 2023. “The Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative: Scientific Objectives and Experimental Design.” *Geoscientific Model Development* 16 (24): 7289–309. https://doi.org/10.5194/gmd-16-7289-2023.

Swingedouw, Didier, Laura Jackson, Aixue Hu, et al. 2026. “TIPMIP-OCEAN Experimental Protocol Phase 1: Tipping Dynamics of the AMOC.” *EGUsphere*, April 8, 1–36. https://doi.org/10.5194/egusphere-2026-1698.

Winkelmann, Ricarda, Donovan P. Dennis, Jonathan F. Donges, et al. 2025. “The Tipping Points Modelling Intercomparison Project (TIPMIP): Assessing Tipping Point Risks in the Earth System.” *EGUsphere*, June 18, 1–52. https://doi.org/10.5194/egusphere-2025-1899.