SPECIAL 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	2024
Project Title:	AMOC decline and recovery under strong warming and overshoot scenarios
Computer Project Account:	spitmehl
Principal Investigator(s):	Oliver Mehling
Affiliation:	Politecnico di Torino, Italy
Name of ECMWF scientist(s) collaborating to the project (if applicable)	–
Start date of the project:	01/01/2023
Expected end date:	31/12/2024

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)	22,500,000	23,991,872	20,000,000	11,200,000
Data storage capacity	(Gbytes)	45,000	?	90,000	80,392

Summary of project objectives (10 lines max)

This Special Project aims at improving our understanding of the long-term evolution of the Atlantic Meridional Overturning Circulation (AMOC) under strong future anthropogenic forcing. Specifically, we investigate the contribution of meltwater input from the Greenland Ice Sheet (GrIS) to AMOC weakening a high-emission scenario (SSP5-8.5) using the EC-Earth3 climate model. To this end, we run two EC-Earth3 initial condition ensembles under SSP5-8.5 forcing until 2300: one in which we prescribe meltwater input from a coupled climate–ice sheet simulation, and one using the default CMIP6 version of EC-Earth3 that does not capture realistic meltwater dynamics.

Summary of problems encountered (10 lines max)

Compared to the original proposal, we decided to prescribe meltwater forcing derived from a recent coupled climate–ice sheet model (CESM2-CISM) simulation instead of using an ad-hoc parametrization for meltwater. Since CESM2-CISM output was only available for the SSP5-8.5 scenario, we decided to focus on this scenario, using the available computational resources to integrate 2x4 ensemble members to at least 2200.

Since we made a small modification to the default CMIP6 version to suppress an unrealistically strong albedo feedback over Greenland under strong warming (see Fabiano et al. 2024), and only limited output variables are available for the SMHI-LENS runs which our project planned to extend, we started all simulations from 2015. This increased the computational cost for each member.

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

We plan to finalize the integration of all ensemble members by September 2024. If the computational resource allow, we will also run one idealized "hysteresis" experiment, reversing the external forcing after 2300.

List of publications/reports from the project with complete references

Mehling, O., Bellomo, K., Fabiano, F., Devilliers, M., von Hardenberg, J., & Corti, S. (2024). The impact of Greenland ice sheet melt on the future North Atlantic ocean circulation, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-11529. https://doi.org/10.5194/egusphere-egu24-11529 [Presentation]

Bellomo, K., & Mehling, O. (2024). Impacts and state-dependence of AMOC weakening in a warming climate. Geophysical Research Letters, 51, e2023GL107624. https://doi.org/10.1029/2023GL107624

Summary of results

1) Greenland meltwater simulations

We conducted two ensembles (“reference” and “meltwater”) of future projections under SSP5-8.5 forcing using the EC-Earth3 model. Each ensemble consists of four members who sample the range of low-frequency AMOC variability at the end of the historical simulations.

Model development and meltwater forcing

The “reference” ensemble used the standard CMIP6 version of EC-Earth3, except for fixing the surface albedo over the present-day Greenland ice sheet to 0.8 (the default ice sheet albedo in EC-Earth). This change was implemented to avoid an unrealistically strong ice–albedo feedback under strong global warming, where melting the default, 10-meter snowpack over Greenland exposed a “bare rock” albedo of 0.24, leading to an unrealistic local temperature increase (Fabiano et al. 2024).

The “meltwater” ensemble used the same EC-Earth3 version as the “reference” ensemble except for the treatment of freshwater from the Greenland ice sheet. In these simulations, we prescribed runoff and calving from a recent fully coupled climate–ice sheet model simulation using CESM2-CISM (Muntjewerf et al. 2020). We followed the implementation of Devilliers et al. (2024) to prescribe meltwater forcing in EC-Earth3.

Greenland runoff in the EC-Earth3 reference simulations, where it stems mostly from excess P–E, reaches about 0.07 Sv in the 23rd century. This is a similar magnitude compared to Greenland runoff in other CMIP6 models. In comparison, runoff in the meltwater simulations reaches more than 0.3 Sv.

AMOC decline

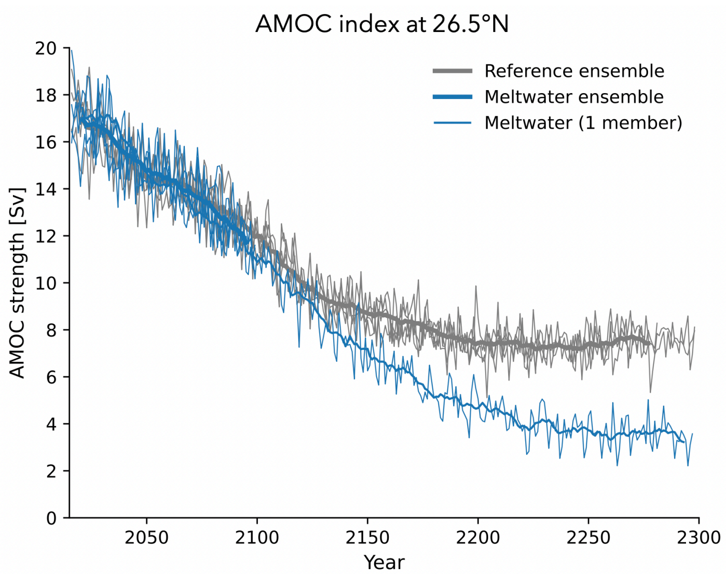

Figure 1: AMOC time series at 26.5°N for all available simulations as of June 2024.

Our primary goal has been the investigation of AMOC decline in response to different freshwater forcing under a high-end CO_2 emission scenario. Over the 21st century, the meltwater ensemble members show a stronger decline than the reference ensemble members by about 1 Sv/century.

So far, we have only extended one meltwater ensemble member until 2300. This simulation shows an enhanced AMOC weakening compared to the reference ensemble, reaching around 4 Sv by the end of the 23rd century, about half as strong as in the reference simulations (Fig. 1).

Currently, we are analysing ocean heat transport, inter-basin effects and water mass transformation in the two ensembles, aiming at improving our understanding of the causes and consequences of the additional AMOC weakening due to increasing Greenland meltwater input.

2) Contribution to "Impacts and state-dependence of AMOC weakening in a warming climate"

In collaboration with the special project SPITBELL, we also contributed one ensemble member to an ensemble of AMOC stabilization experiments with EC-Earth3 (Bellomo & Mehling 2024). In these experiments, we added a uniform positive virtual salt flux in the subpolar North Atlantic and the Arctic Ocean in an *abrupt-4xCO2* experiment, providing buoyancy forcing to counterbalance the AMOC weakening due to the CO_2 increase. The experimental design closely followed the "hosing" protocol of Jackson et al. (2023) and Bellomo et al. (2023) except for the sign of the hosing flux and the warmer background climate, allowing for an analysis of the state-dependence of AMOC impacts.

This project provided one run with a virtual salt flux of +0.4 Sv, completing the two-member ensemble from the SPITBELL project. The three ensemble members combined yielded AMOC time series covering the range of internal variability in the pre-industrial control simulation (Fig. 2), with an AMOC 7 to 10 Sv stronger than in the default *abrupt-4xCO2* experiment.

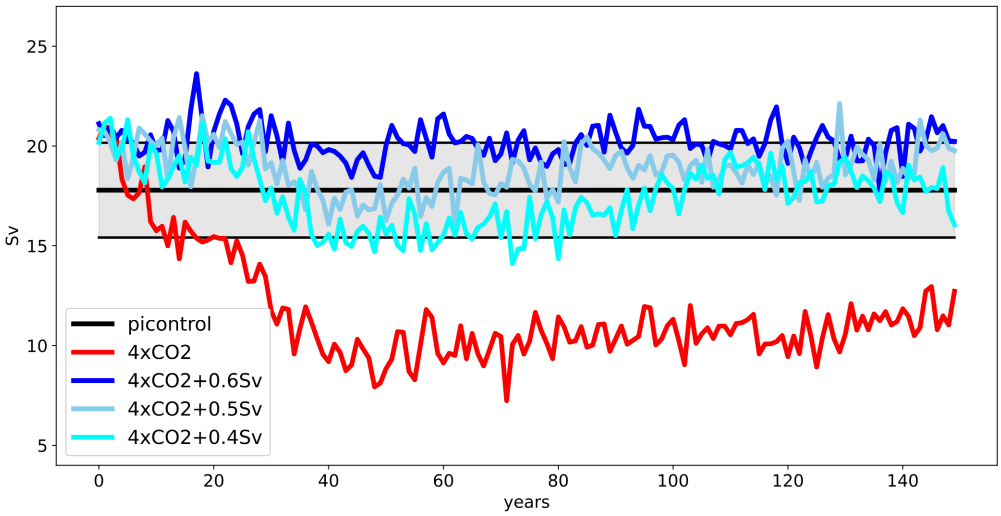

Figure 2: AMOC strength at 26.5°N. The pre-industrial control is represented as the long-term mean (thick black line) and the gray band spans plus and minus 1.5 standard deviations for an estimate of internal variability. The blue/cyan curves are from individual ensemble members of the AMOC stabilization experiments, while the red curve shows the AMOC in the *abrupt-4xCO2*. From Bellomo & Mehling (2024), under CC-BY-NC-ND license.

Using three ensemble members yielded a more robust assessment of the surface climate impacts of AMOC weakening under 4xCO2 forcing. These impacts are described in detail in the publication Bellomo & Mehling (2024).

Additional references

Bellomo, K., Meccia, V. L., D'Agostino, R., Fabiano, F., Larson, S. M., von Hardenberg, J., & Corti, S. (2023). Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model. Climate Dynamics, 61, 3397–3416. https://doi.org/10.1007/s00382-023-06754-2

Devilliers, M., Yang, S., Drews, A., Schmith, T., & Olsen, S. M. (2024). Ocean response to a century of observation-based freshwater forcing around Greenland in EC-Earth3. Climate Dynamics. https://doi.org/10.1007/s00382-024-07142-0

Fabiano, F., et al. (2024). Multi-centennial evolution of the climate response and deep-ocean heat uptake in a set of abrupt stabilization scenarios with EC-Earth3. Earth System Dynamics, 15, 527–546. https://doi.org/10.5194/esd-15-527-2024

Jackson, L. C., 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

Muntjewerf, L., et al. (2020). Greenland Ice Sheet Contribution to 21st Century Sea Level Rise as Simulated by the Coupled CESM2.1-CISM2.1. Geophysical Research Letters, 47, e2019GL086836. https://doi.org/10.1029/2019GL086836