SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	AMOC decline and recovery under strong warming and overshoot scenarios
Computer Project Account:	spitmehl
Start Year - End Year :	2023 – 2024
Principal Investigator(s)	Oliver Mehling
Affiliation/Address:	Politecnico di Torino Corso Duca degli Abruzzi 24 10129 Torino Italy
Other Researchers (Name/Affiliation):	Jost von Hardenberg (Politecnico di Torino) Katinka Bellomo (University of Padua)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

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

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Compared to the original proposal, we decided to prescribe meltwater forcing derived from a recent coupled climate–ice sheet model (CESM2-CISM2) simulation instead of using an ad-hoc parametrization for meltwater. Since CESM2-CISM2 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 extended, we started all simulations from 2015. This increased the computational cost for each member.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

I found the special project framework to be an extremely valuable offer for large computational projects such as those in climate modelling, especially for early-career researchers. Application and reporting were straightforward, and the interactions with ECMWF staff very positive. For the application process, it would be great if the gap between application and project start was a bit shorter than the current 6 months, but in my case, the resources from a late request were sufficient even for a relatively large number of coupled climate model integrations.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

(see following pages)

A comprehensive presentation and discussion of the results obtained within this special project can be found in Chapter 4 ("Impacts of Greenland ice sheet melt on the AMOC in long-term future projections") of the PhD thesis of Mehling (2025), see bibliography. Hence, only a short summary of results is given here.

In this project, we conducted two ensembles of future projections under SSP5-8.5 forcing, with unabated greenhouse gas emissions beyond the 21st century, using the EC-Earth3 model. Each ensemble consisted of four members who sampled the range of AMOC variability at the end of the historical simulations.

Model development and experiment setup

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. 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). In the default version, runoff from the Greenland ice sheet is calculated by distributing excess P–E to coastal grid points, just like the treatment of runoff in non-glaciated regions. In addition, there is a minor contribution from the melt of the snowpack.

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) under SSP5-8.5 forcing until 2300. The spatially resolved freshwater flux fields were remapped conservatively onto the NEMO grid, replacing the default Greenland runoff and calving following the implementation of Devilliers et al. (2024).

Greenland runoff in the EC-Earth3 reference simulations is of similar magnitude compared to many other CMIP6 models, stabilizing at about 0.07 Sv by the mid-22nd century. In comparison, runoff in the meltwater simulations reaches more than 0.3 Sv by 2300 (Fig. 1).

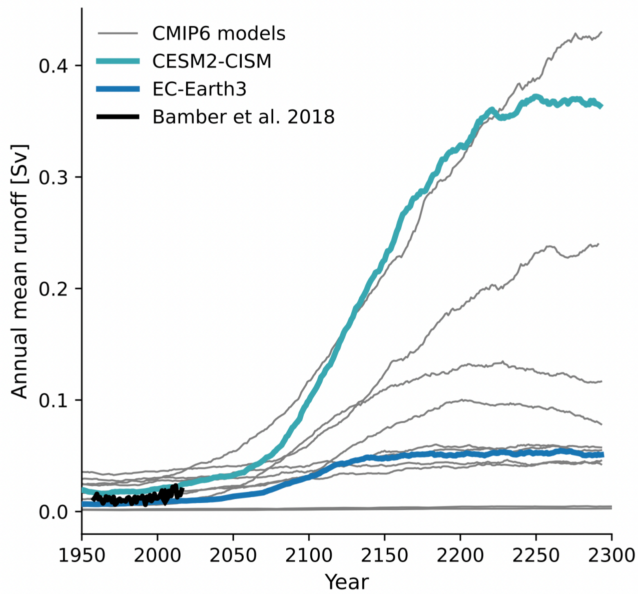

Figure 1: Annual mean runoff from Greenland in historical and SSP5-8.5 simulations until 2300. Grey: individual CMIP6 models, blue: EC-Earth3 reference simulation, cyan: CESM2-CISM runoff prescribed for the EC-Earth3 meltwater ensemble.

AMOC decline

Our primary goal was the investigation of AMOC decline in response to different freshwater forcing under a high-end CO_2 emission scenario. Over the 21st century, the AMOC trend is relatively linear in the SSP5-8.5 scenario, between about –4 and –7 Sv/century in the reference ensemble. The meltwater ensemble members consistently show a statistically significant additional decline by about 1 Sv/century. However, due to the relatively large AMOC variability in EC-Earth3, this is still on the same order of magnitude as internal variability (Fig. 2).

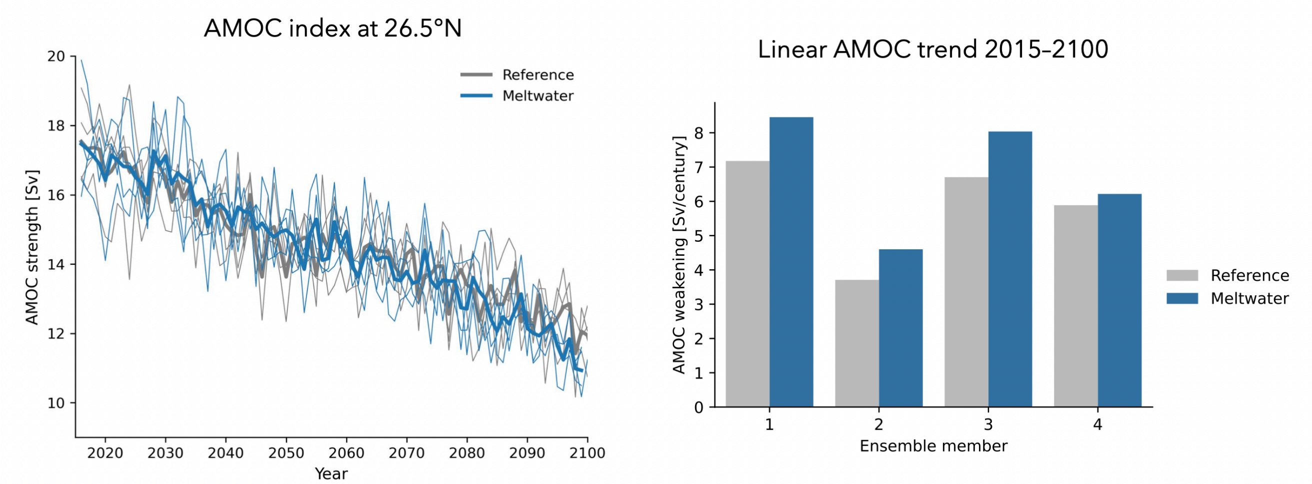

Figure 2: (a) AMOC time series at 26.5°N for all individual ensemble members (thin lines) and ensemble means (thick lines) under SSP5-8.5 forcing until 2100. (b) Linear AMOC trend (2015–2100) for each ensemble member.

We extended all 2x4 ensemble members until 2200. Because of the signal is much larger than internal variability at this point, only selected ensemble members were extended further until 2300. The AMOC weakens to around 4 Sv at the end of the 23rd century under combined CO_2 forcing and Greenland meltwater input, compared to around 8 Sv in the reference simulations with only CO_2 forcing. The physical mechanisms of this additional AMOC decline are analysed in detail in Mehling (2025).

Climatic impacts

The use of an initial condition ensemble and comparatively high atmospheric resolution of EC-Earth3 also allowed to robustly assess the impacts of the meltwater-induced AMOC weakening on the surface climate.

As an example, Fig. 3 shows the impacts of the additional AMOC decline on annual mean surface temperature and precipitation by the end of the 22nd century. These fields exhibit the expected patterns typically associated with AMOC weakening (e.g., Bellomo et al. 2023, Bellomo & Mehling 2024): relative cooling in the Northern hemisphere; a smaller relative warming in the Southern hemisphere, which is only statistically significant in a few regions such as over the Benguela Current; drying throughout most of the Northern hemisphere; and a dry-wet signature around the equator associated with a southward shift of the ITCZ.

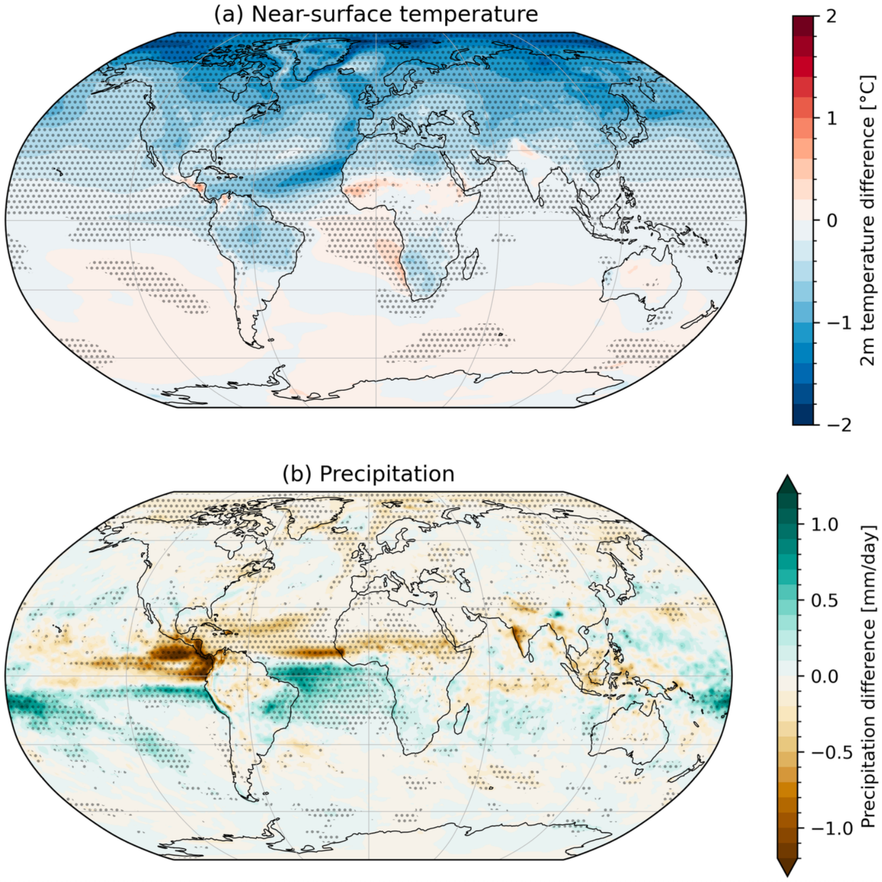

Figure 3: Ensemble mean difference (meltwater minus reference) for (a) near-surface temperature, (b) precipitation at the end of the 22nd century (2170-2200). Regions with significant differences between the ensembles (using a student's t-test with each ensemble member as a sample) are indicated by stippling.

Other simulations

In collaboration with the special project SPITBELL, we also contributed one ensemble member to an ensemble of AMOC stabilization experiments with EC-Earth3. The results of this project are described in the final report of SPITBELL and in the publication of 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

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

List of publications/reports from the project with complete references

Publications:

Bellomo, K., & Mehling, O. (2024). Impacts and State-Dependence of AMOC Weakening in a Warming Climate. Geophysical Research Letters, 51(10), e2023GL107624. https://doi.org/10.1029/2023GL107624

Mehling, O. (2025). Long-term variability and change of the Atlantic Meridional Overturning Circulation in a hierarchy of climate models. PhD thesis, Politecnico di Torino, Turin, January 2025, pp. 59–82. https://hdl.handle.net/11583/2997455
(temporarily also available at https://surfdrive.surf.nl/files/index.php/s/vo5jAB16bANLDrf)

Paper in preparation:

Mehling, O., Bellomo, K., Fabiano, F., Devilliers, M., Corti, S., & von Hardenberg, J. Impacts and reversibility of meltwater-induced future Atlantic overturning changes. In preparation.

Conference contributions/presentations:

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, https://doi.org/10.5194/egusphere-egu24-11529

Mehling, O. (2025). Impacts of realistic Greenland meltwater in future projections with EC-Earth3, EC-Earth General Assembly 2025, Stockholm & online.

Mehling, O., Bellomo, K., Fabiano, F., Devilliers, M., Corti, S., & von Hardenberg, J. (2025). Impacts and reversibility of meltwater-induced future Atlantic Meridional Overturning Circulation changes, EGU General Assembly 2025, Vienna, Austria, https://doi.org/10.5194/egusphere-egu25-9113

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

In late 2024, additional reversibility experiments, in which meltwater and/or CO_2 forcing were reversed, were performed within the special project SPITVACC. These results will also be reported in the paper currently in preparation, “Impacts and reversibility of meltwater-induced future Atlantic overturning changes”.

Besides these additional simulations, no follow-up special project application is foreseen, although we hope that the extensive model output from these simulations can also benefit future studies.