EMI R&D PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Impacts of an AMOC collapse on atmospheric circulation in the Euro-Atlantic area
Computer Project Account:	spitvacc
Start Year - End Year :	2024 - 2025
Principal Investigator(s)	Andrea Vito Vacca
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Other Researchers (Name/Affiliation):	Katinka Bellomo, Oliver Mehling, Giada Cerato

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

This project investigated atmospheric circulation changes over the Euro-Atlantic region associated with an AMOC slowdown and collapse using the state-of-the-art global climate model EC-Earth3. Three sets of experiments were conducted:

a) Water-hosing and fixed-AMOC experiments: The AMOC was artificially weakened or strengthened by imposing positive/negative virtual salinity anomalies under different radiative forcing scenarios.
b) Warming Hole (WH) sensitivity experiments: Sea surface temperatures in the North Atlantic were modified to isolate the atmospheric impacts of the North Atlantic WH, a prominent surface signature of AMOC slowdown (e.g. Caesar et al., 2018).
c) AMOC collapse protocol: The protocol by Van Westen et al. (2024) was applied to induce an AMOC collapse in EC-Earth3-LR.

Summary of problems encountered

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

Compared to the original proposal, resources were reallocated to reduce the focus on the water-hosing/reverse-hosing configurations (exp. a) in order to fully incorporate experiments b) and c).

No major technical problems were encountered during the project.

Experience with the EMI R&D Project framework

I had a highly positive experience with the EMI R&D Project framework. The application procedure was straightforward, and interactions with the ECMWF staff were prompt, supportive, and effective. This framework is exceptionally valuable for climate modeling research, particularly for supporting early-career researchers.

Summary of results

Experiments (a)

We performed a fixed-AMOC experiment by applying a uniform positive virtual salt flux in the subpolar North Atlantic and the Arctic Ocean. This setup stabilizes the AMOC against the weakening induced by an abrupt 4×CO_2 forcing, following the protocol described by Bellomo & Mehling (2024) (Figure 1), extending the simulation up to year 350.

Additionally, we conducted a suite of water-hosing experiments (imposing a negative virtual salt flux in the subpolar North Atlantic and Arctic Ocean) using a protocol analogous to Bellomo et al. (2023), but under varying radiative forcings. Specifically, two water-hosing members were run under the future SSP5-8.5 scenario, and two members were integrated under an abrupt 4×CO_2 external forcing.

The wintertime Euro-Atlantic atmospheric circulation response in the fixed-AMOC experiment is documented in Vacca et al. (2025). As shown in Figure 2, compared to the fixed-AMOC baseline, the weakened AMOC experiment (abrupt 4×CO_2) exhibits a reduced mixed layer depth (MLD; Fig.

2b), pronounced cooling over the North Atlantic (Fig. 2a), and an increased meridional temperature gradient (MTG; Fig. 2c). Consequently, the jet stream intensifies and extends eastward toward Europe (Fig. 2d), accompanied by an enhanced storm track, particularly along its northeastern flank (Fig. 2e). The geopotential height responds with a negative anomaly near the Northern Annular Mode / NAO centers of action (Fig. 2f). Furthermore, Figure 3 demonstrates that the weakened AMOC state features a higher frequency of the positive North Atlantic Oscillation (NAO+) weather regime, alongside a reduced frequency of the Scandinavian Blocking regime.

Data analysis for the remaining future-scenario water-hosing experiments is currently underway.

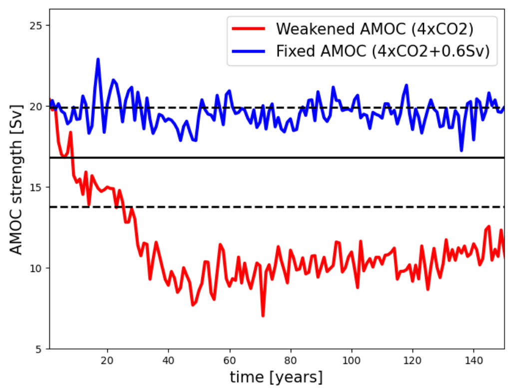

Figure1 (Figure S5 from Vacca et al., 2025): *AMOC strength in the Weakened and Fixed AMOC experiments (EC-Earth3). The time series represent the annual mean maximum of the mass overturning streamfunction in the Atlantic sector below 500 m at 26.5°N. The piControl is represented as the long-term mean (thick black line), while the band between the two dashed lines represents an estimate of the internal variability, computed as plus and minus 2 standard deviations from the long-term mean.*

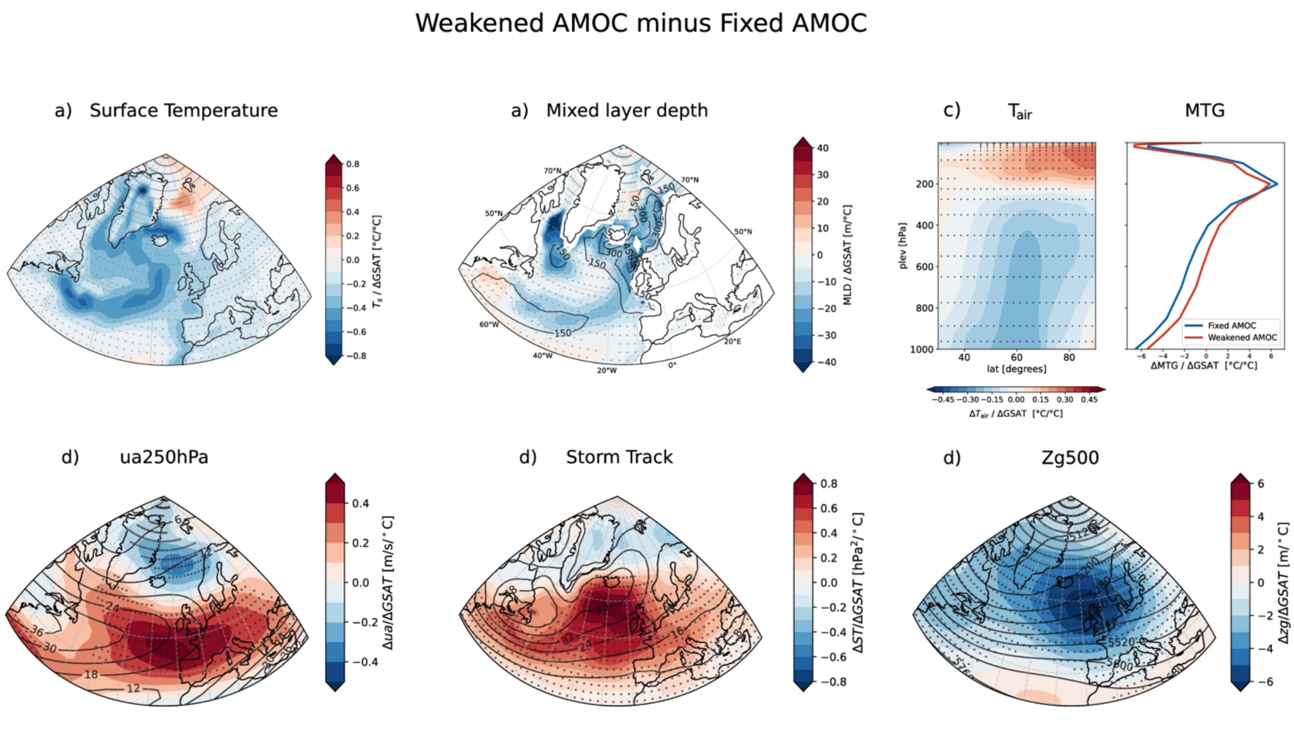

Figure 2 (Figure 9 from Vacca et al., 2025): *Climatological response in the EC-Earth3 Weakened AMOC experiments compared to the Fixed AMOC experiment (normalised by GSAT) in Surface Temperature (a), Mixed Layer Depth (b), Zonal mean air temperature and Meridional Temperature Gradient (c), zonal wind at 250 hPa (d), storm track (e) and geopotential height at 500 hPa (f). Stipplings indicate where the signal is statistically significant. The statistical*

significance is computed with a two-tailed Welch t-test at 95% confidence level between seasonal mean values in the Weakened AMOC and Fixed AMOC experiments for each grid-point.

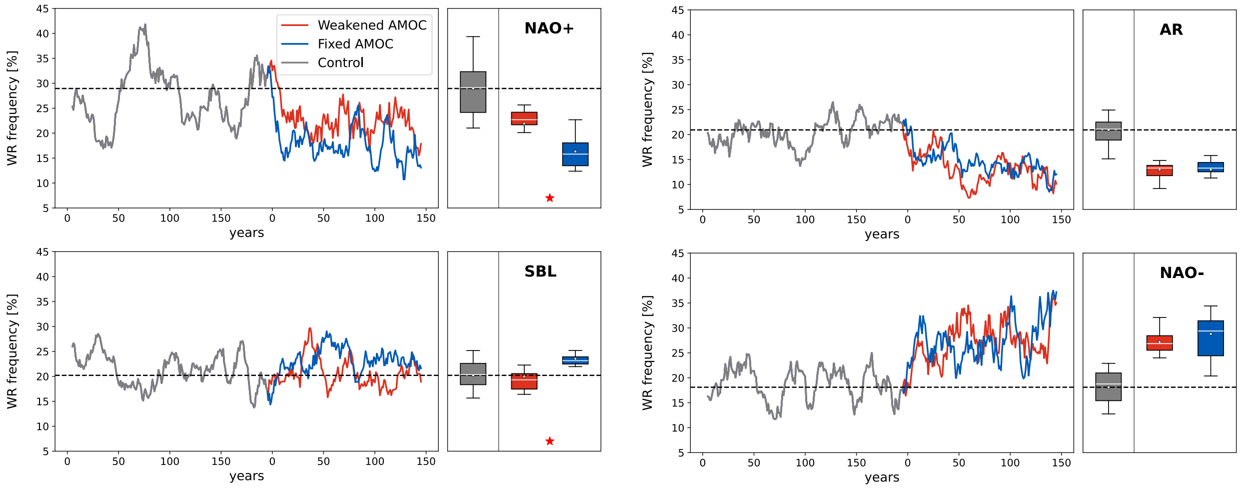

Figure 3 (Figure 10 from Vacca et al., 2025): *On the left hand side of each panel the time series of seasonal mean weather regimes' frequency in the Weakened and Fixed AMOC experiments. Grey lines indicate the last 200 years of the piControl experiment, while red and blue lines the 150-years Weakened and Fixed AMOC experiments, respectively. A 10-year running average smoothing is applied for better visualization. On the right side of each panel boxplots of 10-year mean frequencies in the experiments. Red stars indicate significance difference between the two distributions at the 95% confidence level (Welch two-tailed t-test).*

Experiments (b)

We conducted three atmosphere-only experiments following the AMIP protocol (Gates et al., 1999), modifying the Sea Surface Temperature (SST) boundary conditions to either remove (experiment b2) or enhance (experiment b3) the North Atlantic Warming Hole (WH) in the Subpolar North Atlantic (SPNA). To isolate the atmospheric response to the WH from internal atmospheric variability, a 10-member ensemble was integrated for each experiment under historical radiative forcing spanning the 1970–2014 period. Figure 4 illustrates the long-term SST trends across the three configurations (b1,b2,b3).

Figure 5 shows that, compared to the control experiment without a WH (b2), the WH-perturbed experiments (b1, b3) drive substantial Euro-Atlantic atmospheric circulation changes that emerge significantly above internal variability on multi-decadal timescales. Crucially, the atmospheric response depends non-linearly on the magnitude of the WH forcing: under a stronger WH forcing (Fig. 5, right column), the circulation response is qualitatively different from the weaker forcing case (Fig. 5, left column). Moreover, atmospheric impacts of a stronger WH are remarkably similar to the one found in experiments (a) (Vacca et al., 2025).

A scientific manuscript detailing these findings is currently in preparation.

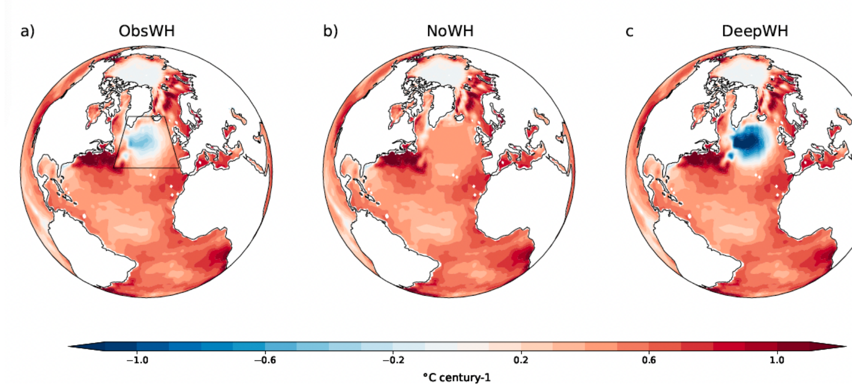

Figure 4: *Long term (1870-2022) linear trends in the observed annual SSTs in experiment b1 (a) b2 (b) b3 (c). The shape in (a) represents the SPNA region (40°–65°N, 50°–10°W).*

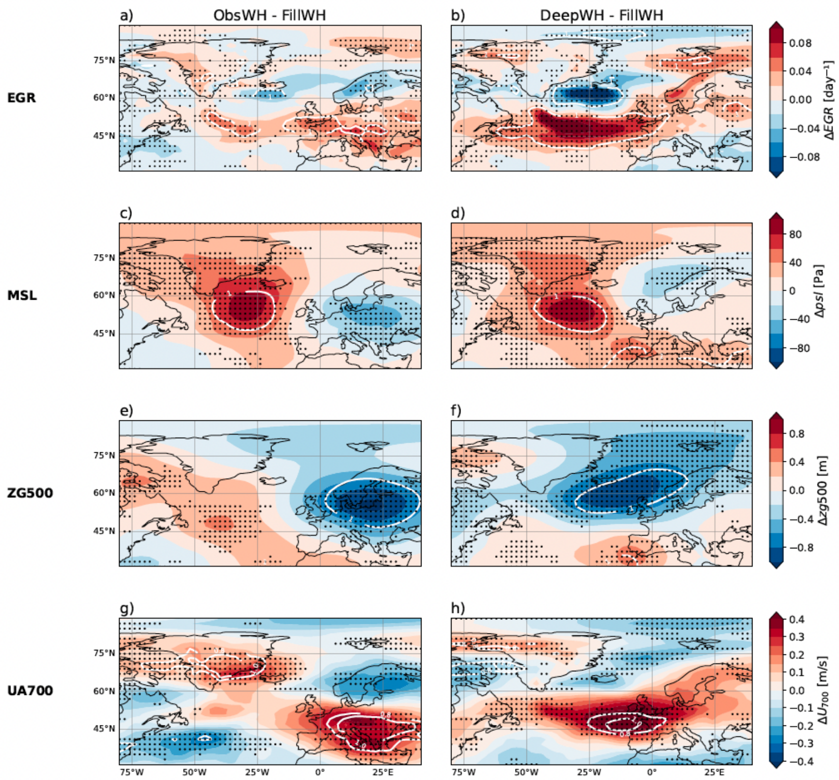

Figure 5: *(a-b) Response in Eady Growth Rate (EGR) in experiments b2 (a) and b3 (b) compared to b1 experiment. Dots indicate points where at least 7 ensemble members show the same sign of the response. The white line represents where the signal-to-noise ratio is greater then 1. Other panels show the same for (c-d) Mean sea level pressure (e-f) 500hPa geopotential height (g-h) 700hPa zonal wind. In (g-h) we indicate also the 0.8 signal-to-noise ratio threshold.*

Experiments (c)

We performed quasi-equilibrium water-hosing experiments (Fig. 6) following the protocol of Van Westen et al. (2024). In these simulations, the freshwater forcing over the 20∘N–50∘N North Atlantic belt was linearly increased at a rate of 0.3 Sv per 1000 years. The three experiments differ in their background climate states: the first was run under pre-industrial conditions, the second under 2025 external radiative forcing (SSP5-8.5), and the third under 2080 radiative forcing (SSP5-8.5).

Following an initial phase of quasi-linear weakening, abrupt non-linear changes in the AMOC strength were detected in all three simulations, indicating the crossing of an AMOC tipping point.

These experiments have been extended under the *spnlmehl* and *spitcera* special projects. Once completed, we will analyze the atmospheric impacts by comparing the final collapse phase against the initial state to evaluate the corresponding response of the Euro-Atlantic circulation.

A scientific paper presenting these results is currently in preparation.

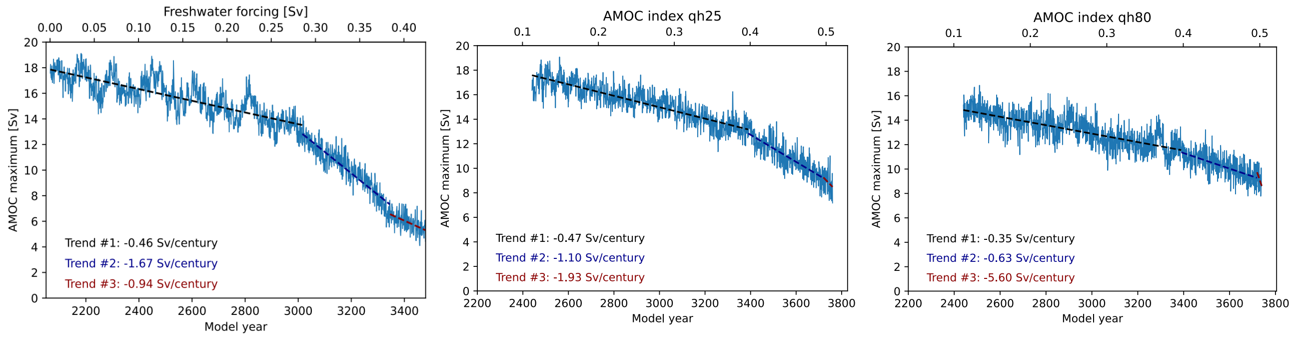

Figure 6*: AMOC strength as a function of freshwater forcing during the quasi-equilibrium experiments with EC-Earth3-LR. **These timeseries have been produced with data of the experiments carried out partially under spitvacc project and extended under spnlmehl** and **spitcera** special projects*.

Main References

René M. van Westen et al. Physics-based early warning signal shows that AMOC is on tipping course.Sci. Adv.10,eadk1189(2024).DOI:10.1126/sciadv.adk1189

Caesar, L., Rahmstorf, S., Robinson, A. et al. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature 556, 191–196 (2018). https://doi.org/10.1038/s41586-018-0006-5

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

Bellomo, K., Meccia, V.L., D'Agostino, R. et al. Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model. Clim Dyn 61, 3397–3416 (2023). https://doi.org/10.1007/s00382-023-06754-2

Vacca, A.V., Bellomo, K., Fabiano, F. et al. On the role of AMOC weakening in shaping wintertime Euro-Atlantic atmospheric circulation. Clim Dynamics 63, 273 (2025). https://doi.org/10.1007/s00382-025-07747-z

Gates, W. L., and Coauthors, 1999: An Overview of the Results of the Atmospheric Model Intercomparison Project (AMIP I). Bull. Amer. Meteor. Soc., 80, 29-56, https://doi.org/10.1175/1520-0477(1999)080<0029:AOOTRO>2.0.CO;2.

List of publications/reports from the project with complete references

Vacca, A.V., Bellomo, K., Fabiano, F. et al. On the role of AMOC weakening in shaping wintertime Euro-Atlantic atmospheric circulation. Clim Dynamics 63, 273 (2025). https://doi.org/10.1007/s00382-025-07747-z

Two other publications for experiments (b) and (c) are in preparation.

Future plans

July 2026

Experiments (c) are being continued under the EMI R&D the project **spnlmehl** “Probing AMOC bistability with EC-Earth3” and project **spitcera**”AMOC tipping and recoverability across Global Warming Levels in EC-Earth3”.

July 2026