LATE REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE: Netherlands

Principal Investigator[1]: Oliver Mehling

Affiliation: Utrecht University

Address: Princetonplein 5, 3584 CC Utrecht, The Netherlands

Other researchers: Henk A. Dijkstra (Utrecht University)

Project Title: Probing AMOC bistability with EC-Earth3

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2026	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:	**2026**	**2027**	**2028**
High Performance Computing Facility [SBU]	40,000,000	–	–
Accumulated data storage (total archive volume)[2] [GB]	110,000	–	–

EWC resources required for project year:	**2026**	**2027**	**2028**
Number of vCPUs [#]	–	–	–
Total memory [GB]	–	–	–
Storage [GB]	–	–	–
Number of vGPUs[3] [#]	–	–	–

Continue overleaf.

---

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

Principal Investigator: Oliver Mehling

Project Title: Probing AMOC bistability with EC-Earth3

Extended abstract

1. Introduction

1.1 Background and motivation

Through its redistribution of heat and carbon, the Atlantic Meridional Overturning Circulation (AMOC) shapes regional and global climate. Therefore, it is pivotal to accurately project future AMOC changes caused by global warming, under which the AMOC is expected to weaken (Fox-Kemper et al., 2021). However, the magnitude of this decline varies widely between different climate models (Weijer et al., 2020), which in turn causes considerable uncertainty in surface climate projections (Bellomo et al., 2021; Hahn et al., 2025). This uncertainty is compounded by processes that are not represented in most current-generation climate models, in particular meltwater due to mass loss of the Greenland ice sheet (Bakker et al., 2016).

The omission of Greenland meltwater especially increases the uncertainty in assessing an abrupt collapse or tipping of the AMOC (Fox-Kemper et al., 2021), as it has been shown in models of various complexity that the AMOC can in principle undergo tipping in response to freshwater forcing (Stommel, 1961; Rahmstorf et al., 2005; van Westen, Kliphuis, et al., 2024, 2025). Despite the robustness of this result, major open questions remain regarding whether such a tipping point could be crossed under future anthropogenic climate change.

One open question is the model dependence of the AMOC tipping point and hysteresis. Rahmstorf et al. (2005) showed that the position of the AMOC tipping point with respect to present-day climate varied widely between different intermediate-complexity models, but this behaviour is poorly understood from theory and has not yet been studied in state-of-the-art (CMIP-class) climate models. This is especially the case for the feedbacks during an AMOC collapse (Vanderborght et al., 2025) and those leading up to the AMOC recovery after reversing the freshwater forcing (van Westen, Jacques-Dumas, et al., 2024). Therefore, it is essential that quasi-equilibrium hysteresis experiments (van Westen & Dijkstra, 2023) are performed with different climate models. To address this gap, in this Special Project, we will carry out a full AMOC hysteresis with a state-of-the-art (CMIP6) climate model, EC-Earth3-LR.

A second open question is whether realistic Greenland ice sheet melt under future warming can trigger such an abrupt AMOC weakening. This is because Greenland meltwater forcing differs fundamentally from that of quasi-equilibrium hosing experiments in terms of magnitude and location as well as the background climate state. State-dependence of the impacts of Greenland meltwater have so far only been studied in idealized Greenland “hosing” experiments (Swingedouw et al., 2015) but not yet with a combination of realistic Greenland meltwater trajectories and future climate change scenarios. This gap will be addressed with the CMIP6 model EC-Earth3, expanding on previous Greenland meltwater simulations with this model under the SSP5-8.5 scenario (Mehling et al., 2025).

1.2 Specific goals of the project

This Special Project will build on existing simulations from the recently concluded Special Projects SPITMEHL (2023–2024) and SPITVACC (2024–2025) in two ways.

In Special Project SPITVACC, we probed the existence of a threshold for an abrupt AMOC collapse in EC-Earth3-LR by performing a quasi-equilibrium hosing experiment (Fig. 1) following the protocol of Van Westen, Kliphuis & Dijkstra (2024). In this simulation, freshwater forcing over the region 20°N–50°N was increased at a rate of 0.3 Sv per 1000 years. After a phase of approximately linear AMOC weakening, an abrupt change in AMOC weakening was found after around 1000 years, hinting at the presence of an AMOC tipping point. This simulation has been completed very recently and comprises a total duration of around 1500 years.

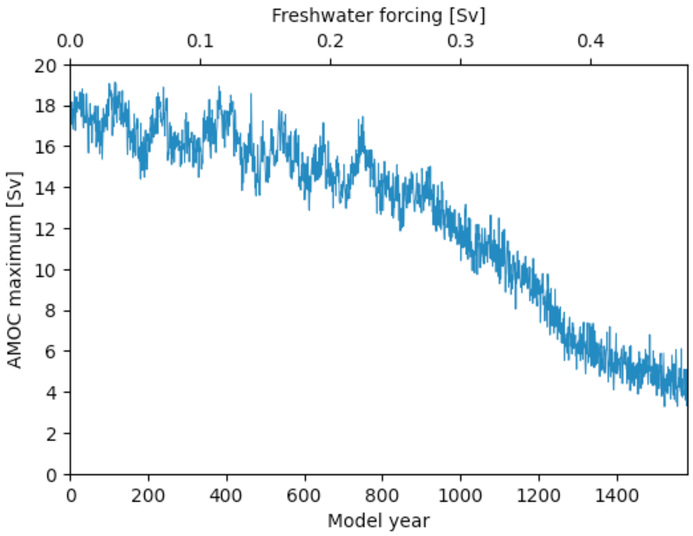

Figure 1: AMOC strength as a function of freshwater forcing during the quasi-equilibrium experiment with EC-Earth3-LR conducted within Special Project SPITVACC.

However, this abrupt AMOC change does not yet demonstrate bistability of the "AMOC on" and the "AMOC off" states – for this, a hysteresis experiment (e.g., Rahmstorf et al., 2005; van Westen & Dijkstra, 2023) needs to be carried out, in which the freshwater forcing is ramped down at the same rate to study the AMOC recovery. In the first part of this project, we therefore propose to carry out this "return" branch of the hysteresis loop. This will make EC-Earth3 only the second contemporary CMIP-class model and the first CMIP6 model to rigorously test AMOC bistability.

In Special Project SPITMEHL, we compared two ensembles of future projections under the SSP5-8.5 scenario with and without realistic Greenland meltwater input. This yielded important insights into the role of Greenland meltwater on the AMOC and the Arctic Ocean under high-end greenhouse gas forcing and substantial Greenland melt (Mehling et al., 2025). However, the SSP5-8.5 scenario, especially in its extension to 2300 with CO2 concentrations reaching more than eight-times pre-industrial levels, has been criticized as an unlikely, "worst-case" scenario (Hausfather & Peters, 2020).

To probe the state-dependence of Greenland meltwater, here we impose strong future Greenland melt in two additional scenarios, following SSP2-4.5 ("middle-of-the-road") and SSP1-2.6 ("sustainability") pathways (O'Neill et al., 2016). In the existing EC-Earth3 simulations (Fig. 2), these two scenarios lead to a smaller AMOC weakening and a nearly full AMOC recovery until 2300, respectively. This will enable to probe the impact of a high-end Greenland meltwater trajectory on a range of different climate and AMOC states. The central question for these experiments will be whether the same amount of Greenland melt can trigger AMOC tipping under less strong greenhouse gas forcing than SSP5-8.5, under which no indications for an abrupt AMOC change or bistability could be identified (Mehling et al., 2025).

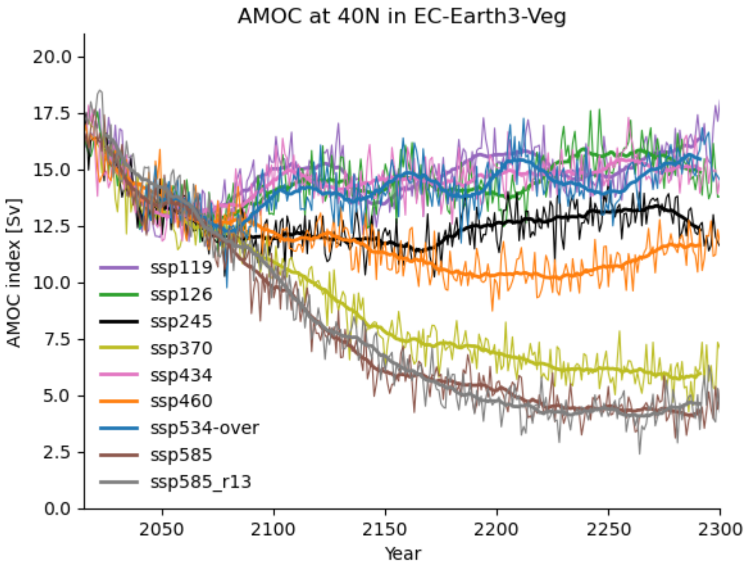

Figure 2: AMOC strength at 40°N in the extended SSP simulations with EC-Earth3-Veg, a very similar configuration to the standard-resolution EC-Earth3. Reproduced from https://www.ecmwf.int/sites/default/files/special_projects/2023/spitmehl-2023-report1.pdf

2. Proposed activities

2.1 Model

We will perform model experiments with EC-Earth3 (Döscher et al., 2022), a state-of-the-art developed by a consortium of European research institutions which participates in CMIP6. EC-Earth3 comprises of the atmospheric model ECMWF IFS cy36r4, the ocean model NEMO3.6 (Madec & NEMO team, 2016) including the LIM3 sea ice component (Rousset et al., 2015), the land surface scheme H-TESSEL (Balsamo et al., 2009) and the coupler OASIS3-MCT (Craig et al., 2017).

For consistency with the existing, previous simulations, EC-Earth3 runs will be carried out at two different resolutions: standard resolution (atmospheric model resolution TL255 ≈ 80 km with 91 vertical levels) for the SSP scenarios with realistic meltwater forcing and low resolution (atmospheric truncation TL127 ≈ 125 km with 57 vertical levels) for the quasi-equilibrium simulations. The reason for using the low-resolution version for the quasi-equilibrium experiments is that the millennial-length runs would be prohibitively expensive with the standard version (around 3x more expensive than the low-resolution version), but the low-resolution version is still well within typical resolutions in CMIP6. Both versions have the same ocean model resolution at around 1°, using an ORCA1 grid with 75 vertical levels for the ocean.

2.2 Simulations

2.2.1 AMOC hysteresis

As outlined in Section 1.2, we will probe AMOC bistability by extending the AMOC collapse simulation with EC-Earth3-LR into a full hysteresis loop. To this end, we will branch off the reverse branch of the hysteresis diagram from year 1500 of the AMOC collapse simulation, i.e., at a freshwater forcing of 0.45 Sv. The freshwater forcing is then ramped down at the same rate of 0.3 Sv per 1000 years. Van Westen & Dijkstra (2023) and Mehling et al. (2026) showed that, in complex ocean models, the bistability range can extend well beyond theoretically expended bounds, e.g., through sea ice feedbacks (van Westen, Jacques-Dumas, et al., 2024). We therefore allocate up to 3000 model years to complete the hysteresis loop.

After completing the hysteresis experiment, we will carry out two equilibrium simulations with fixed freshwater forcing (cf. van Westen, Vanderborght, et al., 2025) for approximately 500 years each on the resulting “On” and “Off” branches. This will allow minimizing residual drift when analyzing the difference between the alternative AMOC states, e.g., in terms of their climatology, climate variability, and AMOC-related feedbacks.

2.2.2 State-dependence of Greenland meltwater impacts

To probe the state-dependence of Greenland meltwater impacts in different global warming scenarios, and especially whether the same amount of Greenland melt can trigger an abrupt AMOC change in lower forcing trajectories than SSP5-8.5, we carry out two simulations under SSP1-2.6 and SSP2-4.5 forcing with the standard-resolution EC-Earth3. For a fair comparison, Greenland meltwater forcing for these runs is the same as in Mehling et al. (2025), which had been derived from the fully coupled climate–ice sheet model CESM2-CISM2 (Muntjewerf et al., 2020).

The simulations are initialized in 2015 and integrated under prescribed greenhouse gas concentrations until 2300 following the ScenarioMIP protocol (Meinshausen et al., 2020; O’Neill et al., 2016), the. The corresponding reference simulations (under the same greenhouse gas forcing but without added Greenland meltwater) are already available from the EC-Earth Consortium.

3. Justification of the computer resources requested

Previous simulations on Atos have determined that the optimal configuration for the standard resolution of EC-Earth3 (TL255L91-ORCA1L75) is obtained using five nodes (490 cores for IFS and 148 cores for NEMO, with one core each for the runoff mapper and the XIOS server). The model typically runs at around 14 simulated years per day (SYPD). Therefore, we estimate that one model year using the standard configuration of EC-Earth3 will use about 19,000 SBU. Accounting for 6-hourly outputs for IFS and monthly outputs for NEMO, we estimate a need for about 40 GB of storage per model year.

For the low-resolution version (TL127L57-ORCA1L75), previous simulations on Atos have been carried out using three nodes (128 cores for IFS and 254 cores for NEMO, with one core each for the runoff mapper and the XIOS server). In this configuration, previous experience has shown that one model year will use about 7,000 SBU. Storage is estimated at about 27 GB per model year, but we will save slightly reduced data for the hysteresis experiment to stay below the 110 TB limit.

In summary, the following resources will be required:

Exp. name	**Resolution**	**Model years**	**Total SBU**	**Total storage (GB)**
Hysteresis	Low-res	3000	21,000,000	55,000
Statistical equilibria	Low-res	2x600 = 1200	8,400,000	32,400
SSP1-2.6 + Meltwater	Standard-res	283	5,377,000	11,320
SSP2-4.5 + Meltwater	Standard-res	283	5,377,000	11,320
Total		≈ 4800	**40,000,000**	110,000

References

Bakker, P., Schmittner, A., Lenaerts, J. T. M., Abe-Ouchi, A., Bi, D., van den Broeke, M. R., et al. (2016). Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters*, *43*(23), 12,252-12,260. https://doi.org/10.1002/2016GL070457

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., van den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623–643. https://doi.org/10.1175/2008JHM1068.1

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nature Communications*, *12*(1), 3659. https://doi.org/10.1038/s41467-021-24015-w

Craig, A., Valcke, S., & Coquart, L. (2017). Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0. *Geoscientific Model Development*, *10*(9), 3297–3308. https://doi.org/10.5194/gmd-10-3297-2017

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., et al. (2022). The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6. *Geoscientific Model Development*, *15*(7), 2973–3020. https://doi.org/10.5194/gmd-15-2973-2022

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., et al. (2021). Ocean, Cryosphere and Sea Level Change. (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al., Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.011

Hahn, L. C., Eisenman, I., Lutsko, N. J., Meccia, V., Mehling, O., & Bellomo, K. (2025). Large Uncertainty in Arctic Warming Driven by the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, *52*(24), e2025GL119720. https://doi.org/10.1029/2025GL119720

Hausfather, Z., & Peters, G. P. (2020). Emissions – the 'business as usual' story is misleading. *Nature*, *577*(7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

Madec, G. & NEMO team. (2016). *NEMO ocean engine* (Notes du Pôle de modélisation de l'Institut Pierre-Simon Laplace (IPSL) No. 27). https://doi.org/10.5281/zenodo.3248739

Mehling, O., Bellomo, K., Fabiano, F., Devilliers, M., Petrini, M., Corti, S., & von Hardenberg, J. (2025, September 29). Limited impact of Greenland meltwater on abruptness and reversibility of future Atlantic overturning changes. arXiv. https://doi.org/10.48550/arXiv.2509.24858

Mehling, O., Vanderborght, E., & Dijkstra, H. A. (2026). Critical freshwater forcing for AMOC tipping in climate models – compensation matters. EGUsphere. https://doi.org/10.5194/egusphere-2025-6215

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Muntjewerf, L., Petrini, M., Vizcaino, M., Ernani da Silva, C., Sellevold, R., Scherrenberg, M. D. W., 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*(9), e2019GL086836. https://doi.org/10.1029/2019GL086836

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Rahmstorf, S., Crucifix, M., Ganopolski, A., Goosse, H., Kamenkovich, I., Knutti, R., et al. (2005). Thermohaline circulation hysteresis: A model intercomparison. *Geophysical Research Letters*, *32*(23), L23605. https://doi.org/10.1029/2005GL023655

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., et al. (2015). The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities. *Geoscientific Model Development*, *8*(10), 2991–3005. https://doi.org/10.5194/gmd-8-2991-2015

Stommel, H. (1961). Thermohaline Convection with Two Stable Regimes of Flow. *Tellus*, *13*(2), 224–230. https://doi.org/10.1111/j.2153-3490.1961.tb00079.x

Swingedouw, D., Rodehacke, C. B., Olsen, S. M., Menary, M., Gao, Y., Mikolajewicz, U., & Mignot, J. (2015). On the reduced sensitivity of the Atlantic overturning to Greenland ice sheet melting in projections: a multi-model assessment. *Climate Dynamics*, *44*(11), 3261–3279. https://doi.org/10.1007/s00382-014-2270-x

Vanderborght, E., van Westen, R. M., & Dijkstra, H. A. (2025). Feedback Processes causing an AMOC Collapse in the Community Earth System Model. *Journal of Climate*, *38*(19), 5083–5102. https://doi.org/10.1175/JCLI-D-24-0570.1

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, *47*(12), e2019GL086075. https://doi.org/10.1029/2019GL086075

van Westen, R. M., & Dijkstra, H. A. (2023). Asymmetry of AMOC Hysteresis in a State-Of-The-Art Global Climate Model. *Geophysical Research Letters*, *50*(22), e2023GL106088. https://doi.org/10.1029/2023GL106088

van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. *Science Advances*, *10*(6), eadk1189. https://doi.org/10.1126/sciadv.adk1189

van Westen, R. M., Jacques-Dumas, V., Boot, A. A., & Dijkstra, H. A. (2024). The Role of Sea-ice Insulation Effects on the Probability of AMOC Transitions. *Journal of Climate*, *37*(23), 6269–6284. https://doi.org/10.1175/JCLI-D-24-0060.1

van Westen, R. M., Vanderborght, E., & Dijkstra, H. A. (2025). A saddle-node bifurcation may be causing the AMOC collapse in the Community Earth System Model. *Earth System Dynamics*, *16*(6), 2063–2085. https://doi.org/10.5194/esd-16-2063-2025

van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2025). Collapse of the Atlantic Meridional Overturning Circulation in a Strongly Eddying Ocean-Only Model. *Geophysical Research Letters*, *52*(6), e2024GL114532. https://doi.org/10.1029/2024GL114532