REQUEST FOR A SPECIAL PROJECT 2026–2028

MEMBER STATE:	Denmark
Principal Investigator[1]:	Marion Devilliers
Affiliation:	Danish Meteorological Institute (DMI)
Address:	Sankt Kjelds Plads 11, 2100 København Ø
Other researchers:	Shuting Yang (DMI), Steffen M. Olsen (DMI), Ilana Schiller-Weiss (DMI), Andrea Gierisch (DMI), Torge Martin (GEOMAR), Tido Semmler (Met Eireann)
Project Title:	Impact of horizontal ocean grid refinement and freshwater fluxes coming from Greenland Ice sheet on AMOC predictability in EC-Earth4 using AGRIF

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]	133,000,000	150,000,000	150,000,000
Accumulated data storage (total archive volume)[2]	[GB]	23,000	46,000	69,000

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: Marion Devilliers

Project Title: Impact of horizontal ocean grid refinement in the ocean and freshwater fluxes coming from Greenland Ice sheet on AMOC predictability in EC-Earth4 using AGRIF

Extended abstract

Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a major component of the global climate system. Its variability and potential long-term weakening are expected to have significant consequences for the North Atlantic, Europe and beyond. While most climate models agree on a weakening trend of the AMOC under anthropogenic forcing, large uncertainties remain regarding its timing, amplitude, and reversibility (Bakker et al., 2025; Ben-Yami et al., 2024; Van Westen et al., 2023). The representation of subpolar gyre dynamics, mesoscale processes, and their role in the transport of freshwater fluxes from Greenland are all critical elements that could impact AMOC behaviour (Schiller-Weiss et al., 2024; Martin et al, 2023; Swingedouw et al, 2022). High-resolution simulations and regionally refined ocean models offer a promising path to improve our understanding of these processes.

This project proposes to use the latest EC-Earth4 configuration with the Adaptive Grid Refinement in Fortran (AGRIF) system to refine the horizontal ocean resolution over the subpolar gyre (50°N–70°N, 65°W–25°W) where convection, boundary currents, and freshwater inputs from the Greenland Ice sheet interact. We aim to assess the influence of realistic freshwater forcing on the AMOC by performing targeted ensemble simulations with enhanced horizontal resolution in the subpolar gyre.

Workplan

Starting from 1900, we will run a 50-year spin-up simulation of EC-Earth4 with ocean grid refinement, then we will perform two 10-member ensembles from **1950 to 2015** following two configurations:

1. **ENS-AGRIF**: EC-Earth4-GCM with 1/12° AGRIF nest in the subpolar gyre, using default parametrizations of the runoff and solid ice discharge from Greenland. The 10 historical ensemble members will be initialized from year 1950 of the spin-up simulation using perturbations of atmospheric initial conditions.
2. **ENS-AGRIF-FWF**: Same configuration but with corrected Greenland freshwater fluxes, following the methodology proposed by Devilliers et al. (2021, 2024).

From **2015 to 2100**, each ensemble will be branched into two scenarios: SSP2-4.5 and SSP5-8.5. This results in four ensemble mean trajectories after 2015. All experiments will be conducted using the EC-Earth4-GCM configuration based on OpenIFS cy48r1, NEMO4.2, XIOS, and OASIS coupler. The AGRIF zoom will be coupled to the global ORCA1 grid, as previously demonstrated in SPIODEA and other refinement projects.

The freshwater forcing applied in the REF-AGRIF-FWF configuration will be based on the new observation-based Greenland runoff and solid ice discharge dataset available at https://zenodo.org/records/15360328. This dataset provides monthly fluxes from 1950 to 2022 at high spatial resolution and is designed for model integration. Using this dataset will ensure full consistency with ongoing experiments from the SPIESEMM Special Project, enabling direct comparison of the climate system response across different EC-Earth configurations. Scenario runs will use meltwater estimate from the coupled climate–ice sheet model CESM2-CISM2 until 2100 following Mehling et al., 2025.

A preliminary test phase in 2026 will ensure numerical stability, efficiency of AGRIF coupling, and reproducibility. The historical ensemble simulations will be carried out from 2026 to early 2027, and the scenario branches will be simulated during 2027–2028.

Justification of resources

High-resolution simulations are essential to realistically represent exchanges between Greenland boundary currents and the interior Labrador Sea - key processes for deep convection and AMOC variability. While 1/4° simulations remain too diffusive, 1/12° resolution enables eddy-driven cross-shelf exchange and improved water mass properties (Hallberg, 2013; Chassignet et al., 2020). Deshayes et al. (2013) demonstrated realistic overturning at 1/12° with careful tuning, and Petit et al. (2023) and Jackson et al. (2020) showed enhanced AMOC sensitivity at eddy-resolving scales. Coupling such resolution with corrected Greenland freshwater fluxes (Devilliers et al., 2021, 2024) offers a unique framework to investigate how meltwater alters stratification, convection, and ultimately the AMOC.

Additionally, long simulations are necessary to capture low-frequency and centennial variability of the AMOC. Studies such as Mehling et al. (2024), Meccia et al. (2023), and Jiang et al. (2021) demonstrate that decadal variability is often superimposed on slower trends or regime shifts that only become apparent over multi-decadal to centennial timescales. This justifies the need for simulations spanning from 1950 to 2100 to correctly sample AMOC internal variability and forced response.

Estimated computational cost of the nested configuration

The current model configuration using the ORCA1 grid (nominal 1° resolution) comprises approximately 120,184 horizontal grid cells and 75 vertical levels, leading to a total of ~9 million ocean grid points. This setup requires approximately **7,000 SBU/year** and produces about **10 GB/year** of output.

For numerical stability reasons, it is not possible to directly nest a 1/12° grid within a 1° global grid using AGRIF; an intermediate refinement is required to ensure a smooth transition and avoid the generation of spurious numerical instabilities at the grid interface. In the proposed configuration, we introduce a **two-level nested refinement** over the North Atlantic subpolar gyre (50°N–70°N, 65°W–25°W). This region will first be refined to 1/4° resolution and then to 1/12°, increasing the total number of horizontal grid cells to ~248,000.

However, the computational cost does not scale linearly with the number of grid points. Because the ocean model (NEMO) is constrained by the CFL condition, smaller grid spacing in the refined regions imposes smaller time steps: the 1/4° nest requires ~4× more time steps than ORCA1, and the 1/12° nest requires ~12× more time steps than ORCA1. We estimate the total computational load as a weighted sum, accounting for both the number of cells in each region and the time-stepping frequency:

Region	Grid cells	Time step factor	Weighted cost
ORCA1 (global)	120,000	×1	120,000
1/4° nest	13,000	×4	52,000
1/12° nest	115,000	×12	1,380,000
Total			**~1.55 million**

Given that the global ORCA1 model alone (120k weighted units) costs 7,000 SBU/year, the full nested setup with ~1.55 million weighted units leads to a projected cost of: SBU_{nested} ≈ 7,000× (1.55M/120k) ≈ **90,400 SBU/year**

This is a conservative upper-bound estimate, assuming full-time activation of both nests. In practice, the effective cost may be lower depending on implementation details (e.g., time-varying nesting, masking, or asynchronous coupling). Nonetheless, this provides a robust basis for resource planning.

Storage Requirements and Strategy

The storage can be scaled the same way, the same way lead, which would lead to 129 GB/year**.** To limit storage costs, we plan to retain **full global outputs at 1° resolution**, and **regional outputs at 1/4° resolution** only within the nested domain (50°N–70°N, 65°W–25°W), which encompasses the subpolar North Atlantic. We do not plan to store outputs from the 1/12° nest. This strategy reflects our primary scientific objective: to investigate the **long-term variability of the Atlantic Meridional Overturning Circulation (AMOC)**, which can be adequately captured at 1° resolution globally, with enhanced detail in the key region where AMOC variability originates. High-frequency or eddy-scale processes, while important, are not the main focus of this project and can be diagnosed through targeted short simulations if needed.The storage cost was estimated by scaling the known output volume of the global ORCA1 configuration (10 GB/year) according to the number of grid points and time steps in the refined 1/4° region, resulting in a total of approximately **14.3 GB/year** for the selected outputs.

The following table summarizes revised estimates of Service Billing Unit and storage per simulated model year of the current EC-Earth4 version available, following the SPNLTUNE-2025 project, and the nest configuration in the project.

Configuration	SBU/year GCM	Storage / model year
TL159/eORCA1	7,000 SBU/year	10 GB / y
TL159/eORCA1+AGRIF	90,400 SBU/year	14.3 GB / y

Total estimation of computationnal ressources

Each ensemble member (1950–2100) represents 151 years. With 2 configurations (with and without freshwater forcing), 10 members each, and 2 scenario branches after 2015, the simulation plan results in:

- Historical: 2 ensembles × 10 members × 65 years = 1,300 years + 50 years (spin-up)
- Scenario: 2 ensembles × 2 scenarios × 10 members × 86 years = 3,440 years
- Total = 4,790 simulated years, each costing ~90,400 SBU/year → ~433M SBU total

  Storage is estimated at ~14.3 GB per year due, leading to ~**69 TB total**.

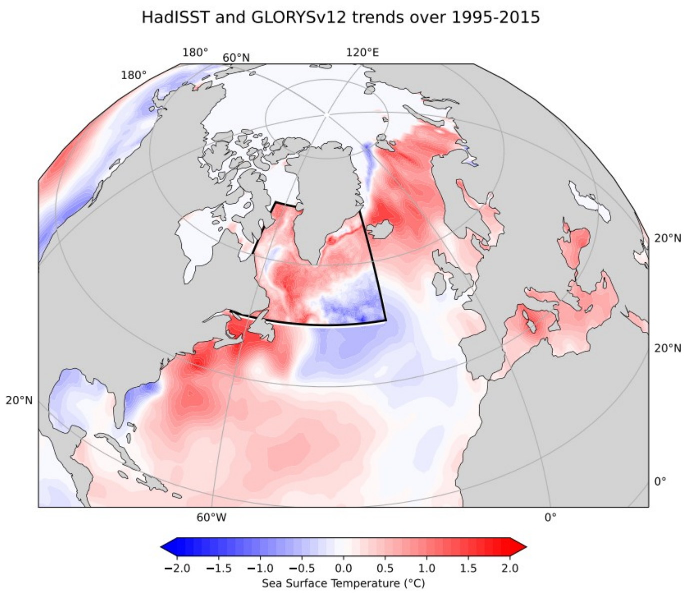

Figure: Sea surface Temperature trends in the subpolar from GLORYSv12 reanalysis (1/12°) and HadISST observational product (1°) between 1993 and 2020, highlighting the target of AGRIF zoom.

Expected outcomes

- Quantitative assessment of how oceanic horizontal resolution affects AMOC variability and trends.
- Evaluation of the role of Greenland freshwater input in AMOC weakening.
- Improved understanding of model resolution requirements to reduce uncertainty in AMOC projections.
- Preparation of EC-Earth4 for participation in CMIP7 with regionally refined capability.
- Data and insights for potential downstream applications in decadal prediction.

Dissemination plan

- Peer-reviewed publications in high-impact climate science journals.
- Presentations at major conferences (EGU, AGU, ICES, CLIVAR).
- Shared datasets and metadata through ESGF and institutional servers (e.g., DMI, BSC).
- Direct contribution to EC-Earth community development and CMIP7 planning.

Conclusion

This project will deliver the first ensemble simulations with EC-Earth4 using AGRIF, allowing for high-resolution ocean refinement over the subpolar gyre. It will also be the first time that realistic Greenland Ice Sheet (GrIS) runoff forcing is applied consistently in scenario ensemble runs within the EC-Earth4 framework. These simulations are designed specifically to assess the impact of GrIS meltwater on North Atlantic deep water formation and AMOC evolution. Unlike previous studies, our approach builds dedicated ensembles to sample internal variability, rather than relying solely on deterministic or single-member experiments. This work is strongly synergistic with the ongoing Special Projects SPIESEMM (focused on EC-Earth system development and evaluation) and SPIEODEA (focusing on downscaling with AGRIF). By combining EC-Earth4's next-generation configuration with novel refinements and ensemble design, the project provides a unique and innovative contribution to the EC-Earth community and broader AMOC predictability efforts.

Bibliography

- Baker, J.A., et al. Continued Atlantic overturning circulation even under climate extremes. Nature 638, 987–994 (2025). https://doi.org/10.1038/s41586-024-08544-0
- Ben-Yami, M., et al. Uncertainties too large to predict tipping times of major Earth system components from historical data. Sci. Adv. 10, eadl4841(2024). DOI:10.1126/sciadv.adl4841
- Chassignet, E. P., et al. Impact of horizontal resolution on global ocean–sea ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2), Geosci. Model Dev., 13, 4595–4637, https://doi.org/10.5194/gmd-13-4595-2020, 2020.
- Devilliers, M., et al. A realistic Greenland ice sheet and surrounding glaciers and ice caps melting in a coupled climate model. Clim Dyn 57, 2467–2489 (2021). https://doi.org/10.1007/s00382-021-05816-7
- Devilliers, M., et al. Ocean response to a century of observation-based freshwater forcing around Greenland in EC-Earth3. Clim Dyn 62, 4905–4923 (2024). https://doi.org/10.1007/s00382-024-07142-0
- Jackson, L.C., Roberts, M.J., Hewitt, H.T. et al. Impact of ocean resolution and mean state on the rate of AMOC weakening. Clim Dyn 55, 1711–1732 (2020). https://doi.org/10.1007/s00382-020-05345-9
- Jiang, W., et al. (2021). Multicentennial variability driven by salinity exchanges between the Atlantic and the arctic ocean in a coupled climate model. Journal of Advances in Modeling Earth Systems, 13, e2020MS002366. https://doi.org/10.1029/2020MS002366
- Martin, T. and Biastoch, A. On the ocean's response to enhanced Greenland runoff in model experiments: relevance of mesoscale dynamics and atmospheric coupling, Ocean Sci., 19, 141–167, https://doi.org/10.5194/os-19-141-2023, 2023.
- Meccia, V.L., et al. Internal multi-centennial variability of the Atlantic Meridional Overturning Circulation simulated by EC-Earth3. Clim Dyn 60, 3695–3712 (2023). https://doi.org/10.1007/s00382-022-06534-4
- Mehling, O., et al. (2024). Centennial-scale variability of the Atlantic meridional overturning circulation in CMIP6 models shaped by Arctic–North Atlantic interactions and sea ice biases. Geophysical Research Letters, 51, e2024GL110791. https://doi.org/10.1029/2024GL110791
- Mehling, O., Bellomo, K., Fabiano, F., Devilliers, M., Corti, S., and von Hardenberg, J.: Impacts and reversibility of meltwater-induced future Atlantic Meridional Overturning Circulation changes, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-9113, https://doi.org/10.5194/egusphere-egu25-9113, 2025.
- Petit, T., Robson, J., Ferreira, D., & Jackson, L. C. (2023). Understanding the sensitivity of the North Atlantic subpolar overturning in different resolution versions of HadGEM3-GC3.1. Journal of Geophysical Research: Oceans, 128, e2023JC019672. https://doi.org/10.1029/2023JC019672
- Schiller-Weiss, I., et al. (2024). Emerging influence of enhanced Greenland melting on boundary currents and deep convection regimes in the Labrador and Irminger Seas. Geophysical Research Letters, 51, e2024GL109022. https://doi.org/10.1029/2024GL109022
- Swingedouw, D., et al. AMOC Recent and Future Trends : A Crucial Role for Oceanic Resolution and Greenland Melting ? Frontiers in Climate, vol. 4, 2022.
- van Westen, R. M., et al. Physics-based early warning signal shows that AMOC is on tipping course. Sci. Adv.10, eadk1189(2024). DOI:10.1126/sciadv.adk1189