REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Ireland

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Project Title:

Improving AMOC Representation in EC-Earth through Enhanced Vertical Coordinate and High-Resolution Nested Domains (Collaboration with UK Met Office)

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.)	2025	
Would you accept support for 1 year only, if necessary?		NO ☒

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	50 MSBU	60 MSBU	
Accumulated data storage (total archive volume)[2]	[GB]	1500 GB	1500 GB	

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

[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.

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Extended abstract

1. Project Title:

Improving AMOC Representation in EC-Earth through Enhanced Vertical Coordinate and High-Resolution Nested Domains (Collaboration with UK Met Office)

2. Principal Investigator:

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3. Co-Investigators:

Tido Semmler (Met Éireann) John Hanley (Met Éireann) Diego Bruciaferri (UK Met Office) Isabella Ascione (UK Met Office)

4. Summary:

The Atlantic Meridional Overturning Circulation (AMOC) plays a critical role in global climate by transporting heat northward. Accurately representing AMOC variability in climate models remains a challenge (McCarthy et al., 2023, Zhao et al., 2024), but is crucial given the large influence of AMOC variability and long-term changes on the climate of north-western Europe (Jackson et al., 2015). Large uncertainties exist also regarding the climate model simulated spatiotemporal structure and intensity of the North Atlantic Warming Hole, a regional cooling phenomenon over the North Atlantic subpolar gyre in a globally warming world (Qasmi, 2023). This project aims to improve AMOC representation in the EC-Earth model by implementing two key enhancements:

- **Enhanced Vertical Coordinate:** We propose implementing the local Multi-Envelope (ME) vertical coordinate system in key regions of the EC-Earth model, particularly around the Greenland-Scotland Ridge. This approach, following Bruciaferri et al. (2024), will improve the representation of crucial AMOC processes like Nordic Sea Overflows by better accounting for the complex bathymetry in these areas. The standard z-coordinate system has limitations in accurately capturing such features (e.g. Legg et al., 2006, Colombo et al., 2020).
- **High-Resolution Nested Domains:** We will employ the UK Met Office's strategy of using two-way high-resolution nested zooms with AGRIF facilitation in the North Atlantic. This will further enhance the representation of key AMOC processes (e.g., Gulf Stream, Greenland-Iceland Seas, Labrador Sea, Mediterranean overflow) within the coarse NEMO-based global ocean component of EC-Earth.

By focusing on these critical aspects of ocean circulation, this project aims to achieve a more realistic representation of AMOC within a 30-year historical coupled ocean-atmosphere simulation. This improved representation will provide a robust foundation for future studies investigating the long-term trends in AMOC and the North Atlantic warming hole, which require simulations exceeding 50 years to overcome inherent variability. Access to ECMWF's high-performance computing resources will be crucial for conducting these high-resolution simulations.

5. Collaborative Strengths

This project leverages the expertise of researchers from both Met Éireann and the UK Met Office, fostering a collaborative approach that strengthens the proposed research in several ways:

- **Complementary Resources:** This collaboration allows us to leverage the strengths of each institution's resources. Met Éireann offers its understanding of the EC-Earth model and its use within the wider climate modeling community. The UK Met Office contributes its established experience with both the ME vertical coordinate system and two-way nesting using AGRIF and their potential for enhancing ocean models.
- **Enhanced Problem-Solving:** Working collaboratively fosters a richer problem-solving environment. By combining perspectives and expertise, the team can anticipate and address potential challenges during the implementation of the ME vertical coordinate system and high-resolution nested domains within the EC-Earth model. This collaborative approach increases the likelihood of achieving a successful and impactful outcome.
- **Knowledge Transfer and Broader Application:** This collaborative project fosters a two-way knowledge exchange. Met Éireann researchers will gain expertise in the UK Met Office's ME vertical coordinate system and AGRIF two-way nesting techniques. Conversely, the UK Met Office will gain experience with the EC-Earth model, which utilizes a different atmospheric model compared to their Unified Model. This cross-pollination of knowledge will not only benefit future ocean modeling advancements in both institutions but also has the potential to inspire broader applications within the climate research community. The project offers a unique opportunity to study the impact of different atmospheric models on a similar ocean component, potentially leading to valuable insights into coupled climate systems.

By working together, this project benefits from the combined expertise, resources, and problem-solving capabilities of both Met Éireann and the UK Met Office. This collaborative approach strengthens the scientific foundation of the project and increases the potential for significant advancements in AMOC representation within the EC-Earth model.

6. Specific Activities:

- Conduct a comprehensive literature review on AMOC representation in climate models, focusing on biases (particularly the North Atlantic warming hole).
- Analyze observational data (temperature, salinity) to identify key AMOC-influencing regions and processes.
- Design and implement the chosen ME vertical coordinate system within relevant regions of the EC-Earth model, working closely with the UK Met Office team.
- Develop high-resolution nested domains using the AGRIF nesting approach within the North Atlantic region of the EC-Earth model, working closely with the UK Met Office team.
- Conduct a series of initial ocean-only test simulations to validate the functionality and performance of the implemented ME system and nested domains within the EC-Earth framework.
- Analyze the test simulations to assess the impact of the ME system and nested domains on the model's representation of relevant oceanographic processes, particularly those influencing AMOC (e.g., overflows, boundary currents, stratification).
- Based on the test simulation analysis, refine the ME configuration and nesting strategy as needed to optimize performance.

7. Methodology:

- The project will utilize a combination of established ocean modeling techniques and innovative approaches.
- Statistical analysis of observational data and model output will be employed to compare AMOC aspects like overflow strengths, boundary current behaviours, and the separation of key currents within the 30-year simulation timeframe.
- Visualization techniques will be used to compare simulated ocean circulation patterns, particularly in AMOC-critical regions, with observations.

8. Project Phases (2 Years):

Phase 1: Development and Implementation (Year 1):

- Focus on activities 1-4 from Section 6, including the literature review, data analysis, implementation of the ME vertical coordinate system, and design of high-resolution nested domains.
- Collaborate with the UK Met Office to ensure compatibility between the implemented ME system and their expertise.
- Implement initial ocean-only test simulations to validate the functionality of the ME vertical coordinate system within EC-Earth.
- Analyze the test simulations to assess the impact of the ME system on the model's representation of relevant oceanographic processes.
- Based on the analysis, refine the ME configuration and nesting strategy as needed.

Phase 2: Evaluation and Analysis (Year 2):

- Conduct the 30-year historical coupled ocean-atmosphere simulation with the enhanced EC-Earth model, utilizing a base resolution of **1/4 degree in the global ocean** and employing **higher-resolution nested domains** within the North Atlantic using the AGRIF nesting approach.
- Analyze the simulated AMOC within the 30-year timeframe, focusing on comparisons with observations in key regions like the overflows, boundary currents, and the Gulf Stream/Nordic Seas separation. We acknowledge that a 30-year timeframe is not sufficient to assess long-term AMOC variability, as demonstrated by studies like Fraser et al. (2021) who reconstructed AMOC variations over 120 years using observations. Our focus here is on the impact of the implemented enhancements on individual components of the AMOC system within this timeframe. This improved model will serve as a valuable foundation for future endeavors investigating long-term trends.
- Evaluate the improvements in representing these AMOC aspects compared to the standard EC-Earth configuration.
- Prepare a comprehensive report summarizing the project methodology, results, and the achieved improvements in AMOC representation within the 30-year simulation timeframe.

Enhancing Ocean Model Fidelity in Critical AMOC Regions:

The proposed high-resolution nested domains using the AGRIF approach will provide a crucial step forward. By focusing computational resources on the North Atlantic, a region with complex bathymetry and key AMOC processes, we can achieve a level of detail that would be computationally prohibitive for the entire global ocean. This targeted approach allows us to:

- **Resolve Mesoscale Ocean Eddies:** AGRIF nesting facilitates simulations that capture mesoscale ocean eddies, critical players in energy transport within the North Atlantic. These eddies play a significant role in the dynamics of boundary currents and overflows, directly impacting AMOC (Chassignet et al., 2021, Colombo et al., 2020).
- **Improve Bathymetry Representation:** The Multi-Envelope (ME) vertical coordinate system offers a significant advantage over the standard z-coordinate system in regions with complex bathymetry, like the Greenland-Scotland Ridge. By allowing the model to better follow the actual underwater topography, the ME system enhances the representation of bottom-intensified currents crucial for AMOC, such as the Nordic Sea Overflows (Bruciaferri et al., 2024).
- **Enhanced Representation of Gravity Currents**: localising (i.e., embedding) a ME vertical coordinate system within the domain of a model otherwise using z-levels can allow one to reduce spurious (i.e., numerical) diapycnal mixing in comparison to standard geopotential levels, therefore improving the representation of oceanic gravity currents and the associated water masses. The Nordic Seas overflows constitute the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). Therefore, using local ME terrain-following coordinates to improve the representation of the Nordic Seas overflows as in Bruciaferri et al. (2024) should allow us to improve the simulation of the AMOC in an eddy permitting geopotential ocean model.

By implementing these advancements, we expect to achieve a more realistic representation of AMOC processes within the EC-Earth model, leading to a more accurate simulation of the Atlantic Meridional Overturning Circulation and its influence on global climate.

SBUs (System Billing Units):

We estimate requiring approximately **50 million SBU in year 1** and **60 million SBU in year 2** for conducting the simulations at the proposed resolutions. These estimates are based on our initial runs of ocean-only simulations of GOSI10 ¼ degree and earlier runs of EC-Earth fully coupled.

Emphasis on AGRIF Efficiency:

It's crucial to highlight the computational efficiency of the AGRIF nesting approach. Compared to running the entire global ocean at a high resolution, utilizing AGRIF with nested domains at this resolution within the North Atlantic region is estimated to save computational resources by an order of magnitude (approximately 20 times). This significant cost reduction allows us to achieve the desired level of resolution in critical AMOC regions while maintaining computational feasibility.

9. Expected Outcomes:

- A more realistic representation of AMOC processes within the EC-Earth model, particularly regarding overflows, boundary currents, and the separation of key currents, evident within the 30-year simulation timeframe. This improvement is facilitated by the application of the ME vertical coordinate system and high-resolution nested domains.
- A 30-year historical coupled simulation with improved AMOC representation, providing a valuable foundation for future studies on long-term AMOC trends and the North Atlantic warming hole. This improved model will serve as a stepping stone for such endeavors, even though this project itself cannot assess those long-term trends.
- Enhanced understanding of the limitations of the standard z-coordinate system and the benefits of the implemented ME vertical coordinate system, particularly in regions with complex bathymetry.

- Improved collaboration between Met Éireann and the UK Met Office through joint research and knowledge transfer, fostering future collaborations in climate modeling advancements.

10. Dissemination Plan:

- Project findings will be presented at relevant international conferences (e.g., European Geosciences Union Meeting, American Geophysical Union Fall Meeting).
- Peer-reviewed publications in high-impact scientific journals focusing on ocean modeling and climate research.
- Project reports will be submitted to ECMWF and made publicly available through appropriate repositories after addressing any confidentiality concerns.
- We will actively engage with the wider climate research community through workshops and presentations to share our knowledge and experience implementing the ME vertical coordinate system and high-resolution nested domains within EC-Earth.

11. Conclusion:

We believe this project will contribute significantly to advancing our understanding of AMOC and its role in global climate. The improved model representation achieved through this project will pave the way for more accurate simulations of future climate change impacts, particularly those related to regional ocean circulation patterns and heat transport. The project also fosters valuable collaboration between Met Éireann and the UK Met Office, leading to knowledge exchange and potential advancements in climate modeling for both institutions.

12. References:

- Bruciaferri, D., Guiavarc'h, C., Hewitt, H. T., Harle, J., Almansi, M., Mathiot, P., & Colombo, P. (2024). Localized general vertical coordinates for quasi-Eulerian ocean models: The Nordic overflows test-case. *Journal of Advances in Modeling Earth Systems*, **16(3)**, e2023MS003893. https://doi.org/10.1029/2023MS003893
- Chassignet, E. P., & Xu, X. (2021). On the importance of high-resolution in large-scale ocean models. *Advances in Atmospheric Sciences*, **38(10)**, 1621-1634. https://doi.org/10.1007/s00376-021-0385-7
- Colombo, P., Barnier, B., Penduff, T., Chanut, J., Deshayes, J., Molines, J.-M., Le Sommer, J., Verezemskaya, P., Gulev, S., & Treguier, A.-M. (2020). Representation of the Denmark Strait overflow in a z-coordinate eddying configuration of the NEMO (v3.6) ocean model: resolution and parameter impacts. *Geoscientific Model Development*, **13(7)**, 3347-3371. https://gmd.copernicus.org/articles/13/3347/2020/
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- Legg, S., Hallberg, R. W., & Girton, J. B. (2006). Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and non-hydrostatic models. *Ocean Modelling*, **11(1)**, 69-97. https://doi.org/10.1016/j.ocemod.2004.11.006
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- Qasmi, S. (2023): Past and future response of the North Atlantic warming hole to anthropogenic forcing. *Earth System Dynamics*, **14**, 685–695. https://doi.org/10.5194/esd-14-685-2023
- Zhao, A., Robson, J., Sutton, R., Lai, M. W. K., Mecking, J. V., Yeager, S., and Petit, T. (2024): Large diversity in AMOC internal variability across NEMO-based climate models. *Climate Dynamics*, **62**, 3355–3374. https://doi.org/10.1007/s00382-023-07069-y

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 10,000,000 SBU should be more detailed (3-5 pages).