REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	Italy
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Project Title:	Sampling AMOC tipping events with a rare event algorithm with a low resolution version of state of the art model

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** spitcini	
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?	YES ☒	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	23,500,000	16,500,000	N/A
Accumulated data storage (total archive volume)[2]	[GB]	55,000	80,000	N/A

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

[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.

Continue overleaf.

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Extended abstract

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).

This project continues the previous Special project (splitcini) titled "Sampling AMOC Tipping Events with a Rare Event Algorithm Using a Low Resolution Version of EC-Earth4." The previous project, which formally started a few months ago, is still in its preliminary phase, so the motivations and scientific goals remain unchanged. As the final tuning phase of the low-resolution version of EC-Earth4 is not yet complete, we are also considering the use of other low-resolution state-of-the-art models for the same purpose.

1. Introduction

Understanding the Atlantic Meridional Overturning Circulation collapse (AMOC) is of key importance for advancing climate science as it controls meridional heat and freshwater transport (Bellomo et al. 2021; Weijer et al. 2019). Anthropogenic climate change is projected to weaken the AMOC due to reduced sea water density in the subpolar North Atlantic (Masson-Delmotte et al. 2023; Smeed et al. 2018), this opens the possibility that the AMOC may pass a tipping point and collapses (Weijer et al. 2019; Lenton et al. 2008; Armstrong McKay et al. 2022; Boers 2021), which the sixth assessment report of the IPCC summarises as a low probability event but with a potentially very high impact on climate (Masson-Delmotte et al. 2023).

This weakening can induce significant regional and global climate impacts, including Northern Hemisphere temperature drops, atmospheric circulation changes, and altered global precipitation patterns (Bellomo et al. 2021; Liu et al. 2020; Jackson et al. 2015; Bellomo et al. 2023).

Typically, AMOC weakenings are studied in climate model simulations by the use of external forcing elements like greenhouse gases (Bellomo et al. 2018), freshwater (Liu et al. 2020; Jackson et al. 2015; Bellomo et al. 2023; Jackson et al. 2022) or surface heat perturbations (Gregory et al. 2016). This allows the analysis of the climatic response to an AMOC slowdown and assess if the system has passed a bifurcation tipping point, so that it would remain in the new collapsed state, following a relaxation of the forcing elements.

On the other hand , some recent studies attribute the internal chaotic variability of the system a key role in triggering an AMOC tipping event (Romanou et al. 2023; Mehling et al. 2023, Cini et al. 2024). The potential occurrence of a complete AMOC tipping solely driven by internal variability, i.e. a noise-induced tipping, has been investigated as well in an oceanic box model (Castellana et al. 2019), and in the PlaSIM-LSG (Angeloni 2022; Fraedrich et al. 2005; Maier-Reimer e Mikolajewicz 1992) intermediate complexity model (Cini et al. 2024). In this latter study a rare event algorithm (see section 3 below for details) was employed on ensemble simulations of the present-day climate to explore the potential for noise-induced tipping of the AMOC, driven exclusively by internal climate variability. In particular, in Cini et al. 2024, the following interesting results were found:

- The algorithm effectively identifies pathways leading to abrupt slowdowns of the AMOC, which are unprecedented in a 2000-year control run. Some of these weakened AMOC states result in a collapsed state without indications of AMOC recovery over multi-centennial time scales.
- The temperature and Northern Hemisphere jet stream responses to these internally induced AMOC slowdowns exhibit significant similarities to those observed in externally forced AMOC slowdowns in state-of-the-art climate models. The initial driver of the AMOC slowdown appears to be Ekman transport induced by westerly wind stress anomalies in the North Atlantic, followed by a complete collapse of oceanic convection in the Labrador Sea.

These findings illustrate that transitions to a collapsed AMOC state solely due to internal variability in a model simulation of the present-day climate are infrequent but theoretically plausible.

2. Scientific goals

In order to assess the robustness of the results obtained with PlaSIM-LSG in Cini et al. 2024 and to gain insights into the physics of the transitions, it is crucial to upgrade the study to a model that captures more realistic ocean dynamics. In this project we aim to continue the investigation of noise-induced Atlantic Meridional Overturning Circulation (AMOC) tippings progressing through a climate model hierarchy with increasing complexity and realism. While the phenomenon has been studied in a box model and an intermediate complexity model, our focus is now on examining a low-resolution state-of-the-art climate model. Our main project is still to use the EC-Earth4 model in the TL63L31-ORCA2Z31 configuration. But other low resolution state-of the art models could be used for this purpose. The scientific questions we aim to address can be summarised as follows:

- Is a rare event algorithm able to sample spontaneous AMOC collapses driven by the internal variability in a state-of-art climate model?
    - If the answer is yes, what is the climate response to a spontaneous AMOC collapse as well as the initial physical processes triggering the AMOC spontaneous collapse?
    - If not, such a result could indicate that the model configuration lacks a stable state of weak AMOC, or that resilience mechanisms inhibit noise-induced tipping, or that adjustments to the rare event algorithm setup are necessary for application to a climate model with a significantly higher number of degrees of freedom.

3. Proposed activities

3.1 The model

We propose to perform simulations using a TL63L31-ORCA2Z31 configuration of the European Community Earth System Model, based on EC-Earth4. This low-resolution model enables large-ensemble simulations with computationally affordable costs. In comparison to the PlaSIM-LSG GCM (Angeloni 2022; Mehling et al. 2022; Cini et al. 2024), the model exhibits notable enhancements in terms of the number of resolved physical processes, grid spatial resolution, and the representation of unresolved physical processes.. The development of EC-Earth4 commenced in 2020 under the EC-Earth consortium (see https://ec-earth.org/ec-earth/ and (Shuting 2021)), and it represents the latest generation of EC-Earth consortium models. EC-Earth4 is based on the OpenIFS atmospheric model and NEMO4 ocean model. The proposed low resolution version of EC-Earth4, featuring approximately 2.8˚ x 2.8˚grid resolution for the atmosphere and 2° x 2° grid resolution for the ocean, currently lacks reference in literature as it is undergoing its final tuning development phase. However, this configuration has already been tested and used for preliminary simulations on ECMWF's Atos supercomputer.

3.2 The rare event algorithm

In order to capture multiple spontaneous tipping events of the AMOC, large ensemble simulations of considerable duration are required. However, conducting extensive ensemble simulations over a considerable duration becomes computationally impractical. To overcome this challenge, following

Cini et al, 2024, we propose the application of a rare event algorithm (Ragone et al. 2020; Ragone et al. 2021) . The algorithm involves a set of killing and cloning rules applied throughout the ensemble simulation's evolution to populate the ensemble with model trajectories featuring rare values of a specified metric. In the case of Cini et al. 2024, the metric is the AMOC value between 46-66°N. The algorithm aims to progressively decrease this metric by cloning ensemble members with a weaker AMOC and eliminating those with a stronger AMOC (refer to the Methods section of the paper for further details). Notably, in this setup where no external forcing is introduced, any tipping is inherently induced by the internal dynamics of the climate system.

The implementation of the algorithm to EC-Earth4 will be straightforward. The algorithm interacts with the model only via its output at the end of each year of simulation, in particular in this case by selecting ensemble member trajectories based on their AMOC index. It then rearranges restart files for the following year of simulation. In addition, a new version of the algorithm is under development for EC-Earth3 (see Ragone 2023).

3.3 Simulations

Since noise-induced tippings were found in a given configuration of the algorithm in Cini et al. 2024, we aim to reproduce the same experiments. We estimate that a control run simulation of the model will be completed at the end of 2024. For these simulations computational resources are provided with the precious special project ("spitcini"). The rare event algorithm has some parameters that need to be tuned in order to obtain the strongest AMOC decline. From the beginning of 2025 we plan to perform 5 distinct 70-year test simulations, each with 100 members, to investigate the simulation's evolution, considering different values of the parameter controlling the algorithm's selectivity. The most suitable value is the one demonstrating the most pronounced decrease in the AMOC index during the test simulation.

Upon obtaining a satisfactory parameter value, our next step involves conducting four independent simulations diverging from four distinct initial states of the control run. Each simulation is structured in two segments:

1. "Rare event simulation". 120-years performed with the rare-event algorithm activated . This segment of the simulation consists of a large ensemble of 100 members.
2. "Recovery simulation". Additional 180 years performed with the algorithm deactivated. This phase enables us to scrutinise the system's unrestricted evolution, determining whether the AMOC index undergoes recovery or progresses toward a collapsed state Based on results from Cini et al 2024, we estimate that a simulation with 20 members is sufficient for this purpose.

4. Justification of the requested computer resources

We estimate that by the end of the year 2024 the control run simulations described in the previous Special project will be completed. These simulations are expected to require 24 TB of storage, which will be utilized during this project.The full project is scheduled to conclude by the end of 2026.

The model, with the proposed TL63L31-ORCA2Z31 configuration, has already been run on Atos with 2 nodes (256 cores). A proper scaling test has not yet been carried out , but we can give a reasonable estimation considering the results of this test simulation. Approximately 28 CHPSY are needed, which results in 500 SBU per simulated year. While, considering monthly outputs, 650 MB (600 MB for the ocean and 50MB for the atmosphere) of data storage are needed per simulated year.

	Experiment	Duration	Ensemble members	Number of simulations	Total years	Total resource (approx)	Total data storage (approx)
Year 1	Rare event	120	100	3	36,000		
	Recovery	180	20	3	10,800		
Total year 2 (total data storage is year 1 + 24 TB control run)					46,800	23,500,000 SBU	55 TB

	Experiment	Duration	Ensembl e members	Number of simulations	Total years	Total resource (approx)	Total data storage (approx)
Year 2	Rare event	120	100	2	24,000		
	Recovery	180	20	2	7,200		
Total year (total data storage is year 1 + year 2)					31,600	16,500,000 SBU	80 TB

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