REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Sweden

Principal Investigator[1]: Qiong Zhang

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Project Title: Transient simulations with EC-Earth model for centennial to millennial climate variability study

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**SEZHAN	
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]	60,000,000	60,000,000	60,000,000
Accumulated data storage (total archive volume)[2]	[GB]	100,000	100,000	100,000

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.

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).

In our previous project (2022-2024), we utilized the EC-Earth3 model and conduct a set of transient simulations from the early to late Holocene and explored the multi-centennial variability of the climate system. Because the research project "Invetigating multi-centennial climate variabiliy using the Earth System Model" (funded by the Swedish Research Council VR) using this HPC resource started is ongoing and will end in 2027, the planned Holocene transient simulations have not been completed during the HPC project 2022-2024, necessitating their continuation in the coming years. Therefore, this proposal seeks to continue these simulations through 2025-2027, focusing on further uncovering the mechanisms behind this variability and incorporating new scientific insights and methodologies.

Scientific background and aims

Understanding the mechanisms behind observed climate variability is crucial for assessing the roles of internal variability and external forcing in the climate system. The challenge lies in differentiating these components from the observational record, as observed climate changes result from both internal dynamics and external forcings such as solar radiation and volcanic eruptions. Previous studies have identified multi-centennial scale climate variability, but pinpointing their causes remains difficult. Long-term climate model simulations offer a valuable perspective, enabling us to isolate internal variability and understand how external forces modulate these patterns.

In this project, we focus on centennial to millennial variability, which has been difficult to study due to the limited length of instrumental records and the complexity of internal climate dynamics. Our preliminary results based on an 8000 years Holocene transient simulation have already identified distinct multi-centennial variability (around 150-300 years cycles) and millennial variability (around 1500 years cycle) over the last 8000 years.

Using the piControl simulation, we conclude that this variability is an internal feature modulated by the AMOC (Cao et al., 2023). Our analyses demonstrate that the multi-centennial variability of AMOC in our model is sustained by positive feedback from perturbation advection of mean salinity gradients, the negative feedback from mean advection of salinity anomalies, and enhanced vertical mixing in the subpolar ocean.

We further analyze and investigate the role of external forcing in this multi-centennial climate. Firstly, basing on three 2000-year simulations using the EC-Earth3-LR configuration under three varying CO_2 forcing (280, 400 and 560 ppm), we observe that multi-centennial variability in global mean surface air temperature is prominent across all three experiments, with the most pronounced effects occurring in the North Atlantic and the Arctic region. This low-frequency variation is hypothesized to be driven by fluctuations in AMOC. We propose that the multi-centennial variability in AMOC constitutes a self-sustained intrinsic mode within the North Atlantic basin (Cao et al., 2023). This mode is primarily driven by the salinity advection feedback mechanisms in the subtropical-subpolar North Atlantic and exhibits an oscillation period ranging from 200 to 300 years. Notably, this oscillation mode presents in all three different CO_2 simulations, appearing to be independent of climate states. However, in the warmer climate (400 and 560 ppm), the amplitude of the variability is suppressed and the oscillation period also changes. The manuscript based on this study is submitted to the *Journal of Climate* (Cao et al., 2024). We will further analyze and investigate the role of actual external forcing during the Holocene in this multi-centennial climate variability using the Holocene transient simulations.

Additionally, the previous 8000-year transient simulation started from 8 ka BP to facilitate comparisons with other model results. However, this setup missed the important 8.2 ka event. Therefore, we plan to run these ensemble simulations from 9 ka BP to investigate whether the 8.2 ka event can be simulated without other forcings, thereby improving our understanding of how internal variability and external forcing impact these variabilities.

Scientific question and hypotheses

This project intends to mainly answer the following two main questions:

1. **Is multi-centennial climate variability primarily an intrinsic internal oscillation or is it caused by external forcing?**
2. **How does external forcing impact the multi-centennial climate variability?**

The results from our 3000-year PI control simulation have shown distinct 200-year cycles, originating from the high-latitude North Atlantic (Cao et al., 2023). Similar findings from other PI control runs with EC-Earth3-veg suggest that model resolution is not decisive in generating this cycle. The sensitivity experiments with different CO2 levels (280, 400, and 560 ppm, each simulated for 3000 years) further confirm that multi-centennial variability is an intrinsic internal oscillation, the amplitude and period may change under the different forcings (Cao et al., 2024, to be submitted). We will further analyse the Holocene transient simulations with full forcing to examine the evolution of power spectrum in the last 9000 years and compare with the evolution observed in the paleo proxy data.

Our Holocene transient simulations, with varying orbital and GHG forcing, indicate the presence of multi-centennial variability. We will further analyse simulations that include volcanic forcing to verify its impact on this variability. Our Holocene simulations without volcanic forcing have provided initial insights, but to comprehensively understand this influence, we plan to conduct additional simulations incorporating reconstructed volcanic forcing.

One interesting finding from analyzing our first 8 ka simulation is that while the AMOC dominates centennial to multi-centennial variability in the Northern Hemisphere, the Southern Ocean exhibits millennial climate variability with a 1500-year oscillation linked to the variability of Antarctic Bottom Water (AABW) (Zhou et al., in preparation, see the progress report). We will continue investigating these distinct phenomena and mechanisms in our 9 ka ensemble simulations.

With the new findings from the completed simulation, we add another question:

3. **What controls the millennial climate variability and how do these centennials to millennial variability contribute to the climate events (8.2 k, 4.2 k, green Sahara collapse at 5.5 k, 2.8 k etc)?**

Simulation Plan

To keep the consistency, we will continue to use the CMIP6 version of EC-Earth3-veg-LR for our planned runs. For the new simulations, we focus on the natural external forcing such as orbital, GHG and volcanic forcing, and we removed the pre-industrial land-use module in the dynamical vegetation model LPJ-GUESS, which is a default setup for the CMIP6 version of EC-Earth3. Our continued simulation plan includes:

1. **Ensemble simulations with different AMOC initial conditions:** To explore the role of the AMOC in Holocene climate evolution, we will run three ensembles starting from 9 ka BP, each with different initial AMOC conditions (strong, neutral, weak). These simulations will use orbital forcings and updated GHG forcing.
2. **Simulation including volcanic forcing:** To assess the role of volcanic forcing on multi-centennial variability, we will perform simulations with reconstructed volcanic forcing throughout the Holocene.

Justification of the computing resources

In the current setup for EC-Earth3-veg-LR, we used 256 cores for IFS, 256 cores for NEMO, 64 cores for LPJG-GUESS, 1 core for XIOS and 1 core for RUNOFF, in total of 578 cores for the coupled model, based on testing, the optimal configuration for running the model on the ATOS platform is 4 compute nodes, which corresponds to 1024 cores. It cost 17473 SBU for one model year simulation.

The planned Holocene transient ensemble simulations have been running on Swedish NSC and ECMWF HPC resources since 2022. The total cost for 8000 years will be 68 million SBU, we use 8 million SBU from current HPC project (2022-2024) and request 60 million SBU per year for 2025-2027. The estimated monthly output (cmorised) is 35 TB in total, we will cmorise the model output to monthly mean data and transfer the processed data to local storage in Sweden for extensive analysis, we apply 100 TB storage every year for data process and analysis.

Reference

Cao, N., Zhang, Q., Power, K., Schenk, F., Wyser, K., and Yang, H.: The role of internal feedbacks in sustaining multi-centennial variability of the Atlantic Meridional Overturning Circulation revealed by EC-Earth3-LR simulations. *Earth and Planetary Science Letters, 621,* https://doi.org/10.1016/j.epsl.2023.118372, 2023.

Cao, N., Zhang, Q., and Power, K.: Suppressed multi-centennial variability of AMOC under higher CO_2 levels, to be re-submitted to *Journal of Climate*, 2024.

Zhou, P., Zhang, Q., and Shi, Z.: Bond events and 1500 year cycles in EC-Earth Holocene transient simulation, manuscript in preparation, 2024.