

SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year 2026

Project Title: Holocene climate variability in EC-Earth3 transient simulations

Computer Project Account: SPSEZHAN

Principal Investigator(s): Qiong Zhang

Affiliation: Department of Physical Geography
Stockholm University

Name of ECMWF scientist(s) collaborating to the project
(if applicable)

Start date of the project: 2025-01-01

Expected end date: 2027-12-31

Computer resources allocated/used for the current year and the previous one (if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	60.000.000	13.589.470	36.000.000	25.632.885
Data storage capacity	(Gbytes)	8000	8000	8000	8000

Summary of project objectives (10 lines max)

We aim to investigate multicentennial climate variability, long-term climate evolution, and abrupt climate transitions using the Earth system model EC-Earth. The main focus is on long transient simulations of the Holocene and the Last Interglacial, as well as targeted sensitivity experiments for past warm climates. During the reporting period, the project has continued the analysis of the 8 ka Holocene transient simulation, which has provided the basis for studies of low-frequency variability, AMOC-related climate dynamics, and hydroclimate changes relevant to past societal development. In parallel, the project has supported model experiments for the mid-Pliocene and Miocene, extending the use of EC-Earth to other warm climate states. These simulations are used to improve our understanding of the mechanisms of long-term climate change and to assess the relevance of past climate states for future climate projections.

Summary of problems encountered (10 lines max)

No major technical problems were encountered during the reporting period. The main challenge remains the large volume of data generated by long transient and ensemble Earth system model simulations, which requires substantial storage capacity for restart files, diagnostics, post-processing, and publication-related analysis. This has been handled through the combined use of ECMWF and NAISS resources.

Summary of plans for the continuation of the project (10 lines max)

1. We will continue the Holocene transient ensemble simulations initiated from different AMOC states in order to investigate the mechanisms of multicentennial climate variability and the role of ocean–atmosphere–vegetation feedbacks in abrupt hydroclimate transitions.
2. We will further analyse the existing Holocene simulation output for studies related to the Late Bronze Age collapse, the 4.2 ka hydroclimate event, and the Green Sahara collapse.
3. We will continue the Last Interglacial transient simulation and prepare new simulations with EC-Earth4 for the PMIP/CMIP7 Assessment Fast Track, including the abrupt-127k experiment.
4. We will continue using ECMWF and complementary NAISS resources for model production, data storage, diagnostics, and analysis.

List of publications/reports from the project with complete references

The publications listed below since project year July 2025 have acknowledged the HPC and data support from ECMWF. Some simulations may have done during the previous years. The name(s) from our group is in **bold**.

1. **Power, K., Zhang, Q., Axelsson, J.,** and Ljungqvist, F. C.: Internal hydroclimate variability and the decline of the Classic Maya Civilisation, *Quaternary Science Reviews*, 382, 109974, <https://doi.org/10.1016/j.quascirev.2026.109974>. 2026.
2. Zhou, X., Yang, K., Yang, H., and **Zhang, Q.**: Self-sustained multicentennial oscillation of the Atlantic meridional overturning circulation in two-hemisphere box models, *Climate Dynamics*, 64, 30, [10.1007/s00382-025-07947-7](https://doi.org/10.1007/s00382-025-07947-7), 2026.
3. Matos, F. D. I. A. O., Stepanek, C., Harig, S., Streffing, J., **Zhang, Q., Wang, Z., Power, K., Semmler, T., Sidorenko, D., Scholz, P., Danilov, S., Gravis, P., and Lohmann, G.**: Modeling the Late Pliocene with AWI-CM3 as a contribution to PlioMIP3 core experiments, *Global and Planetary Change*, 257, 105196, <https://doi.org/10.1016/j.gloplacha.2025.105196>, 2026.
4. **Power, K., Oliveira Matos, F. D. A., and Zhang, Q.**: Late Pliocene ice sheets as an analogue for future climate: a sensitivity study of the polar Southern Hemisphere, *Earth System Dynamics*, 16, 1845–1863, <https://doi.org/10.5194/esd-16-1845-2025>, 2025.
5. **Werner, N., Wang, Z., Werdelin, L., and Zhang, Q.**: East African uplift as a catalyst for Middle Miocene faunal transitions, *Science Advances*, 11, eadx6569, doi:10.1126/sciadv.adx6569, 2025.

6. **Han, Z., Werner, N., Wang, Z., Li, X., Yao, Z., and Zhang, Q.:** Miocene African topography induces decoupling of Somali Jet and South Asian summer monsoon rainfall, *Nature Communications*, 16, 7172, 10.1038/s41467-025-62186-y, 2025.
7. **Power, K.:** Uneven future greening across the northern high latitudes: Regional responses to rising CO₂, *Ecological Modelling*, 508, 111193, <https://doi.org/10.1016/j.ecolmodel.2025.111193>, 2025.

Summary of results

The project has made substantial scientific progress during the reporting period through the use of EC-Earth simulations and associated data analysis workflows.

1. 8000-year long Holocene transient simulation and multicentennial variability

A major focus during the period has been the analysis and exploitation of our long transient Holocene simulation with EC-Earth-VEG-LR. These simulations, spanning 8,000 years, have provided the basis for a series of scientific studies addressing low-frequency internal variability, ocean–atmosphere coupling, hydroclimate evolution, and abrupt regional changes. The model results have contributed directly to several peer-reviewed publications published during the reporting period. These include work on internal hydroclimate variability and the decline of the Classic Maya civilisation (Power et al., 2026, *Quaternary Science Review*), moisture variability in eastern North America (Salonen et al., 2025, *Nature communication*), and Holocene changes in the frequency of multi-year ENSO events (Lu et al., 2025, *Nature Geoscience*). Together, these studies demonstrate that the long transient simulations provide a unique framework for investigating how slowly varying external forcing interacts with internal climate variability across regional and global scales.

An important scientific advance from the project has been the continued investigation of centennial to multicentennial variability in the Holocene climate system, especially variability linked to the Atlantic Meridional Overturning Circulation (AMOC). Our transient simulations and long preindustrial control runs revealed pronounced low-frequency variability, motivating a set of ensemble simulations initialized from different AMOC states. These simulations have supported the development of a stronger mechanistic understanding of AMOC-related variability and its climatic impacts. During the reporting period, this line of research contributed both to a published modelling study on self-sustained multicentennial AMOC oscillations (Zhou et al., 2026, *Climate Dynamics*) and to a major manuscript currently under review in *Nature communication*, which proposes that quasi-stationary interhemispheric radiative forcing muted AMOC variability and enabled the abrupt mid-Holocene Green Sahara collapse. This directly addresses the central objective of our VR-funded effort on simulating the Green Sahara and diagnosing the processes responsible for the abrupt regime shift around 5.5 ka.

The same simulation framework has also been used to investigate past hydroclimatic disruptions relevant to human societies. Two manuscripts currently under revision extend the scientific output of the 8 ka transient simulation: one examines Holocene ocean–atmosphere coupling and Mediterranean sensitivity to Atlantic circulation in relation to the Late Bronze Age collapse (*Science Advances*, in press), and the other studies how orbital forcing modulated hemispheric energy balance and preconditioned the 4.2 ka hydroclimate event (*Communication Earth & Environment*, in review). These studies further illustrate the value of the NAISS-supported

simulations for linking large-scale climate dynamics to regionally expressed hydroclimate changes and societally relevant environmental transitions.

2. PlioMIP Mid-Pliocene experiments

Beyond the Holocene work, the resources have also supported model experiments addressing other warm climate periods, in line with the project goal of understanding climate responses under boundary conditions very different from today. In particular, sensitivity experiments and PlioMIP-related analyses have contributed to new publications on the role of Late Pliocene ice sheets in shaping Southern Hemisphere climate (Power et al., 2025, *Earth System dynamics*). These results reinforce our earlier conclusion that slow Earth system feedbacks, rather than direct CO₂ radiative forcing alone, are crucial for understanding hydroclimate and temperature responses in warm climates. This line of work is highly relevant for evaluating long-term climate sensitivity and feedback strength in future warming scenarios.

3. Sensitivity experiments on uplift of Eastern African topography during Miocene

The project has also generated important results from Miocene sensitivity experiments focused on eastern African topography. These experiments resulted in two high-impact publications during the reporting period: one showing that East African uplift during Miocene (~25 ma) acted as a catalyst for Middle Miocene faunal transitions (Werner et al., 2025, *Science Advance*), and another demonstrating that Miocene African topography induced a decoupling of the Somali Jet and South Asian summer monsoon rainfall (Han et al., 2025, *Nature Communication*). These studies highlight the broad applicability of the EC-Earth framework and the importance of NAISS-supported paleoclimate experiments for understanding interactions among topography, circulation, ecosystems, and regional climate.

Overall, the reporting period has been scientifically very productive. The simulations and associated storage have underpinned a substantial body of output, including multiple peer-reviewed papers in leading journals and several major manuscripts under review or revision. These achievements are directly aligned with the original project description: they improve understanding of the behaviour of the climate system under past forcing conditions, clarify mechanisms behind abrupt and low-frequency climate variability, and strengthen the basis for evaluating climate model performance and future climate projections.