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	2025
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)	20.000.000	25.039.244	20.000.000	5.861.538
Data storage capacity	(Gbytes)	50000	50000	50000	38520

Summary of project objectives (10 lines max)

We aim to investigate the role of dynamic vegetation in modulating climate variability over the past millennium using the EC-Earth3-LR coupled with the LPJ-GUESS dynamic vegetation module. Two past1000 transient simulations are performed: one with dynamic vegetation enabled and one with prescribed vegetation. Both simulations include time-varying external forcings such as volcanic eruptions, solar variability, land-use changes, and greenhouse gas concentrations. The goal is to quantify how interactive vegetation alters the response of the climate system to external forcings and contributes to internal variability throughout the past millennium. In addition, we also perform a transient simulation starting from 130 ka to investigate long-term climate evolution during the Last Interglacial onset, providing broader context for interpreting Holocene variability.

Summary of problems encountered (10 lines max)

No problems encountered.

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

1. To better understand the contribution of individual forcings to climate variability during the past millennium, we plan to perform a set of sensitivity experiments based on the past1000 setup. These include transient simulations with volcanic forcing, land-use change, and greenhouse gas variations removed individually. Comparing these runs with the fully forced past1000 simulation will help quantify the role of each forcing in shaping decadal- to centennial-scale climate variability.
2. The ongoing transient simulation starting from 130 ka has currently reached year 4083 and will be extended to cover the full Last Interglacial period. This will allow us to capture the climate evolution during the early and peak phases of the interglacial.

List of publications/reports from the project with complete references

The publications listed below since project year July 2024 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. **Zhengyao Lu, Anna Schultze,** Matthieu Carré, Chris Brierley, Peter O. Hopcroft, Debo Zhao, Minjie Zheng, Pascale Braconnot, Qiuzhen Yin, Johann H. Jungclaus, Xiaoxu Shi, Haijun Yang, **Qiong Zhang**: Increased frequency of multi-year El Niño–Southern Oscillation events across the Holocene, *Nature Geoscience,* 18, 337–343, https://doi.org/10.1038/s41561-025-01670-y, 2025.
2. **Zhenqian Wang, Qiong Zhang, Jie Chen, Zixuan Han:** Differential Vegetation Feedback on the Global Land Monsoon System during the Mid-Holocene and Last Interglacial. *Advances in Atmospheric Sciences*, https://doi.org/10.1007/s00376-024-4284-6, 2025.
3. **Power, K. and Zhang, Q.**: The impacts of reduced ice sheets, vegetation, and elevated CO2 on future Arctic climates. *Arctic, Antarctic, and Alpine Research, 56*(1), 2433860. https://doi.org/10.1080/15230430.2024.2433860, 2024.
4. Gaetani, M., Messori, G., Pausata, F. S. R., Tiwari, S., Alvarez Castro, M. C., and **Zhang, Q.**: Mid-Holocene climate at mid-latitudes: assessing the impact of Saharan greening, *Clim. Past*, 20, 1735–1759, https://doi.org/10.5194/cp-20-1735-2024, 2024.
5. **Berntell, E., Zhang, Q.:** Mid-Holocene West African monsoon rainfall enhanced in EC-Earth simulation with dynamic vegetation feedback. *Clim Dyn*, https://doi.org/10.1007/s00382-024-07262-7, 2024.

Summary of results

The preliminary results summarized below are based on two sets of Last Millennium simulations using EC-Earth3: one with the dynamic vegetation model activated and the other with prescribed vegetation. These simulations allow us to evaluate the role of vegetation–climate feedbacks in modulating climate variability over the past millennium. In addition, a transient simulation starting from 130 ka has been initiated to investigate the climate evolution leading into the Last Interglacial. The experiment is ongoing, but initial results already show clear multi-centennial oscillation cycles. We also run a set of idealized sea level sensitivity experiments during Last Interglacial to assess the impact of sea level changes on climate.

1. Last Millennium transient simulation with EC-Earth-LR (Wang et al., and Tove et al., in preparation)

We conducted two sets of past1000 experiments using EC-Earth3-LR, one with LPJ-GUESS enabled and the other without LPJ-GUESS, to investigate the role of dynamic vegetation in climate variability over the past millennium (850 CE – 1850 CE). These simulations include reconstructed solar forcing, volcanic activity, greenhouse gas concentrations, ozone, and land-use changes, providing insights into the interactions between vegetation and climate.

The simulations successfully reproduce major historical climate events such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) (Figure 1), indicating that the model captures long-term temperature variability well. Results show that volcanic forcing is the dominant driver of decadal- to centennial-scale cooling events, consistent with volcanic activity reconstructions. Moreover, the inclusion of dynamic vegetation reveals a buffering effect, with vegetation mitigating part of the climate response to volcanic eruptions.

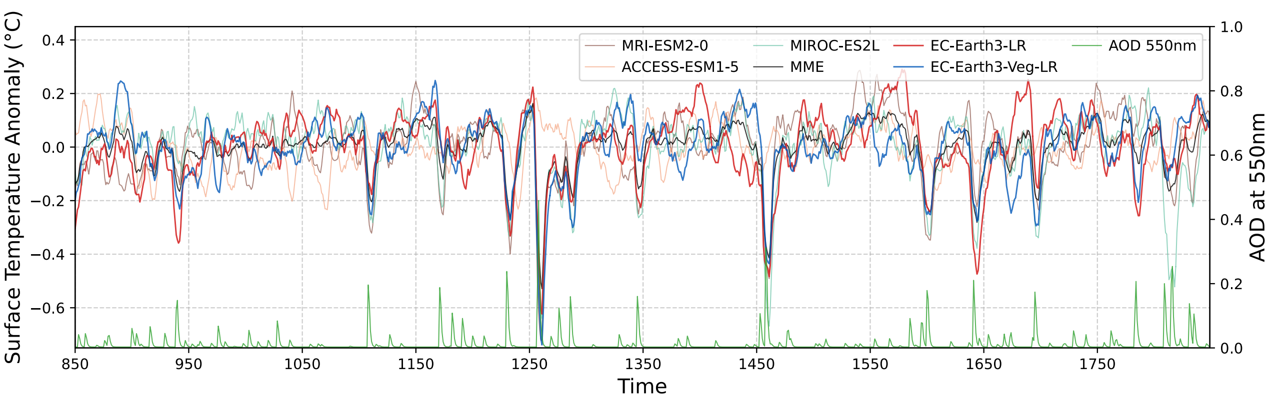

Figure 1 Global mean temperature anomalies from the LMVT (orange) and LNVT (red) experiments, with and without a coupled LPJ-GUESS, respectively, along with AOD at 550 nm (green).

2. Last Interglacial transient experiments

We conducted a transient simulation starting from 130 ka using EC-Earth3-Veg-LR to investigate the climate evolution and variability leading into the Last Interglacial. The experiment includes time-varying orbital forcing and greenhouse gas concentrations. Preliminary results show a gradual global warming trend from 130 ka to approximately 127.8 ka, followed by a relatively stable climate state with embedded multi-centennial oscillations (Figure 2). These fluctuations suggest that the model captures internally generated variability under slowly evolving external forcings. This simulation provides valuable context for understanding early Last Interglacial climate dynamics and supports future analyses of feedback mechanisms and model–proxy comparisons.

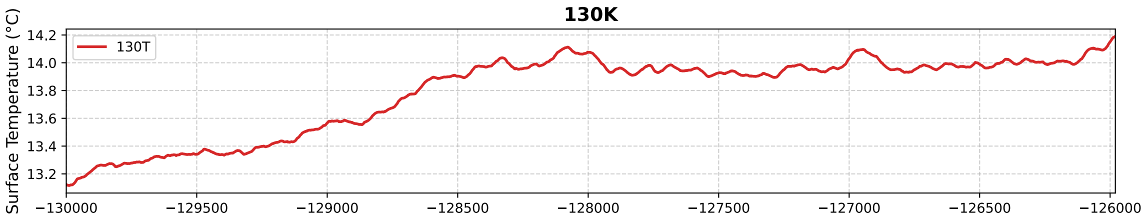

Figure 2 Global mean temperature evolution in the 130T simulation.

3. Last Interglacial sea level sensitivity experiments

To assess the climatic impact of sea level rise during the LIG, we performed a series of idealized experiments using EC-Earth3-Veg-LR with prescribed global mean sea level increases of 5 m and 10 m relative to the present-day. These simulations isolate the effects of bathymetric change while keeping other forcings constant.

Compared to PI, the LIG experiments with or without sea level rise show significant changes in ocean circulation and surface temperature. In particular, sea level rise leads to a freshening of the North Atlantic and salinity increase in the Southern Ocean, contributing to a strengthened Atlantic Meridional Overturning Circulation (AMOC; Figure 2). Despite the enhanced AMOC, the +5 m and +10 m experiments exhibit overall cooler surface temperatures compared to the LIG simulation without sea level rise, indicating that sea level rise alone can introduce a net cooling effect.

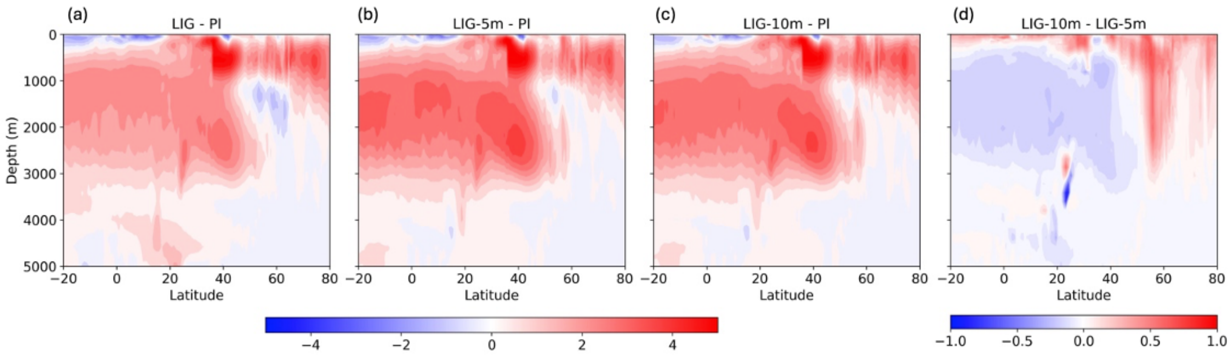

Figure 3 AMOC anomalies of LIG (a), LIG+5 m (b), and LIG+10 m (c) relative to the pre-industrial (PI) simulation. The rightmost panel shows the difference between LIG+10 m and LIG+5 m (d).

These results emphasize that sea level change—through its influence on bathymetry, coastline geometry, and oceanic pathways—can substantially reshape both circulation and climate, even in the absence of changes in external forcings. Sea level must therefore be considered a key boundary condition in paleoclimate modeling frameworks and future CMIP7 experimental designs.