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	2023
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:	2022-01-01
Expected end date:	2024-12-31

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	20.000.000	20.000.000	10.533.237
Data storage capacity	(Gbytes)	50000	50000	50000	44060

Summary of project objectives (10 lines max)

We aim to perform and analyse several-thousand-year-long simulations for different past periods, such as an unforced long pre-industrial control simulation, and forced transient Holocene and Last Interglacial simulations in which we have observed the existence of such multi-centennial variability. The length of these simulations allows to detect the mechanism of slow physical processes with robust statistical assessment.

Summary of problems encountered (10 lines max)

No problems encountered.

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

1. Although several studies suggest that agriculture already began in the Holocene, characterized mainly by non-permanent agriculture (slash-and-burn) from 6000 BP until 3000 BP. To separate the effect of anthropogenic land-use on Holocene climate variability, we turn off all human land use modules, and run another transient experiment without any human activity interference. By isolating the climate system from anthropogenic influences, we can analyze the internal variability and the impact of natural external forcings on the climate over multi-centennial timescales.
2. Our research project on this topic is still ongoing and we will continue the planned simulations in the upcoming project, which is described in the new HPC request for 2025-2027.

List of publications/reports from the project with complete references

The publications listed below since project year July 2023 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. **Chen, J., Zhang, Q.**, Lu, Z., Duan, Y., Cao, X., Huang, J., and Chen, F.: Reconciling East Asia's mid-Holocene temperature discrepancy through vegetation-climate feedback, *Science Bulletin*, https://doi.org/10.1016/j.scib.2024.04.012, 2024.
2. **Han, Z., Power, K.**, Li, G., and **Zhang, Q.**: Impacts of mid-Pliocene ice sheets and vegetation on Afro-Asian summer monsoon rainfall revealed by EC-Earth Simulations, *Geophysical Research Letters*, 51, e2023GL106145, https://doi.org/10.1029/2023GL106145, 2024.
3. Hällberg, P. L., **Schenk, F.**, Jarne-Bueno, G., Schankat, Y., **Zhang, Q.**, Rifai, H., Phua, M., and Smittenberg, R.H.: Branched GDGT source shift identification allows improved reconstruction of an 8,000-year warming trend on Sumatra. *Organic Geochemistry, 186*, 104702. https://www.sciencedirect.com/science/article/pii/S0146638023001481, 2023.
4. **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.
5. Tian, Y., Fleitmann, D., **Zhang, Q.**, Sha, L., Wassenburg, J., **Axelsson, J.**, Zhang, H., Li, X., Hu., J., Li, H., ZHao, L., Cai, Y., Ning, Y., and Cheng, H.*:* Holocene climate change in southern Oman deciphered by speleothem records and climate model simulations. *Nat Commun* **14**, 4718, https://doi.org/10.1038/s41467-023-40454-z, 2023.

Summary of results

The scientific results from above listed paper 4 and two manuscripts in preparation are summarized below. Our simulation data are also used for other projects (Paper 1 and 2) and shared to the collaboration projects on paleoclimate research (Paper 3 and 5).

1. Holocene transient simulation with EC-Earth-veg-LR (Zhang et al., in preparation)

As we reported last year, we have finished one Holocene transient simulation with EC-Earth-veg-LR in 2022. The results are promising, the multi-centennial climate variability with a 200-year power spectrum peak is evident in our 8000 years simulation (Fig.1).

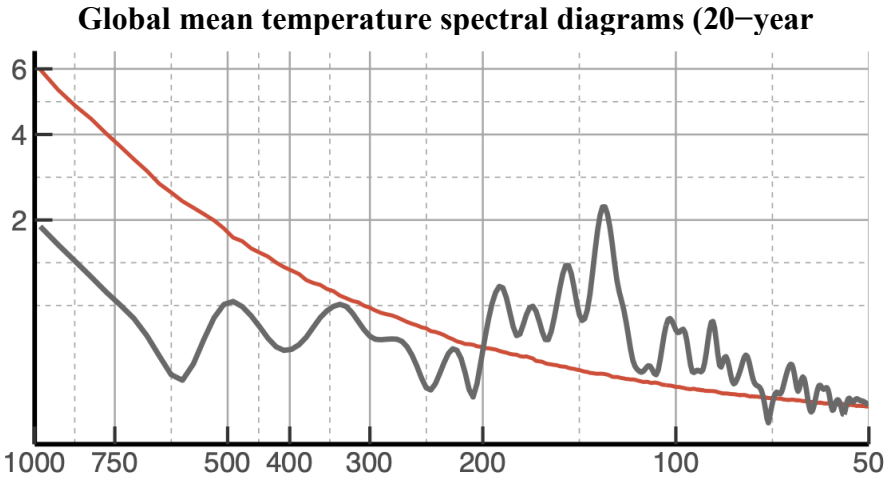

Figure 1. Spectral diagrams and 95 % red noise significance level of global mean temperature filtered with a 20-year low- pass filter from transient Holocene model simulations.

2. Mechanism study with a 3000-year piControl simulation (Cao et al., 2023)

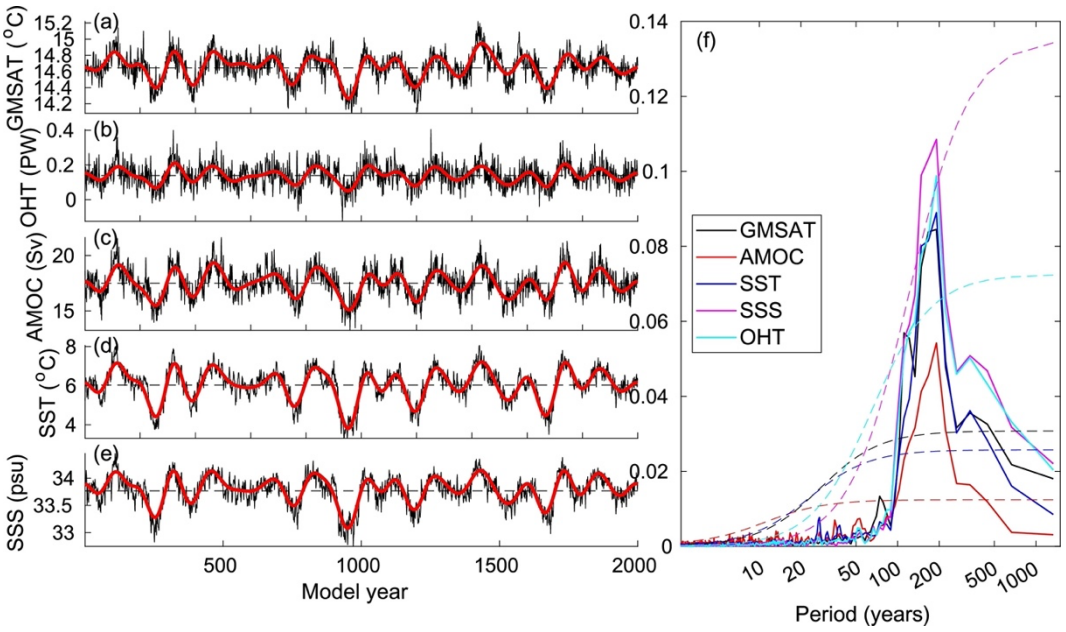

Figure 2. (a~e) Time series of global mean surface air temperature (GMSAT), ocean heat transport crossing 40°N in the Atlantic (OHT, 1 PW = 1015 Watt), AMOC index, sea surface temperature (SST) and sea surface salinity (SSS) averaged over the subpolar area, along with the low-pass filtered series (red curves, using Lanczos method with 201 weights and a 100-year cutoff period); (f) Power spectra of these corresponding time series.

To explain the mechanisms behind this multi-centennial variability, we leveraged both transient and equilibrium experiments. While the 8k transient experiment provides insight into how the climate responds to changing external forcings, we also analyzed the last 3000 years of data from the piControl equilibrium experiment. The piControl with its constant external forcing, allows us to investigate the internal variability of the climate system.

In the piControl experiment, we also observed significant multi-centennial oscillations, spectrum analyses of these time series reveal comparable spectra with a distinct peak around 200 years (Fig. 2). This oscillation originates predominately from the North Atlantic and displays a strong association with the Atlantic Meridional Overturning Circulation (AMOC).

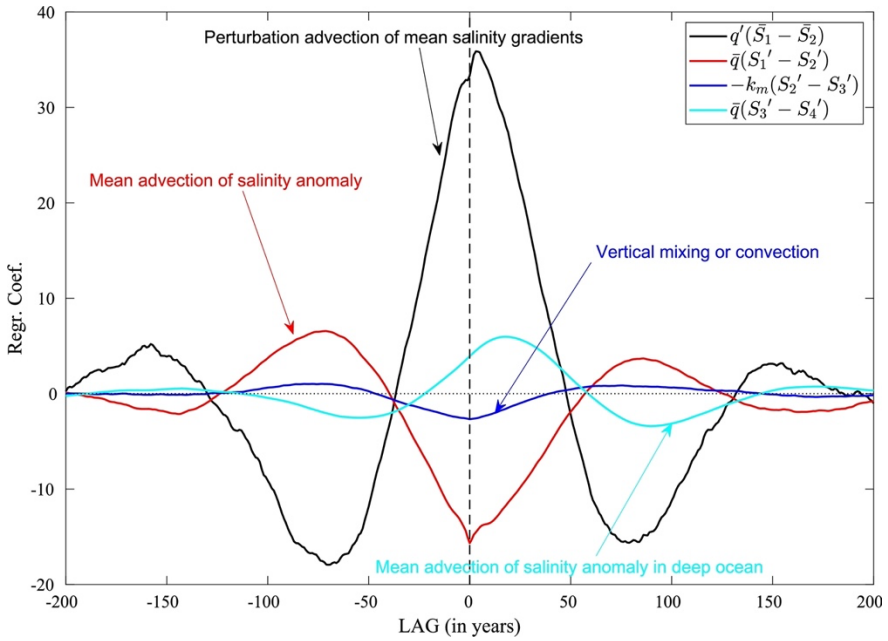

Figure 3. Regression of three direct terms (black, red and blue curves) contributing to seawater salinity variations in Box (Box represents the subpolar upper layer from (50 - 80°N, 0-300 meters deep, between 70°W to 10°E)), and one indirect term (cyan curve) indicating the southward flow related to the lower branch of the AMOC, onto the time series of salinity in Box.

These results 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 (Fig. 3). We will further analyze and investigate the role of external forcing in this multi-centennial climate variability using the Holocene transient simulations.

3. **Multi-millennial variability and climate events (Zhou et al., in preparation)**

As shown in Figure 4, our Holocene transient simulation also captured several notable events observed in paleo proxy data, such as the 4.2k and 2.8k events. Bond proposed that these events occur with a periodicity of approximately 1000-1500 years. To investigate whether our data exhibits similar long-term cycles, we applied an 800-year low-pass filter to the global mean temperature. Through this filtering, we found a clear oscillation with a period of about 1500 years, indicating that our results align with Bond's proposed periodicity.

Based on these findings, in the next phase of our work, we will continue to delve into this dataset to uncover the mechanisms behind this multi-millennial variability. By further analyzing the data, we aim to gain a deeper understanding of the factors driving these long-term climate cycles.

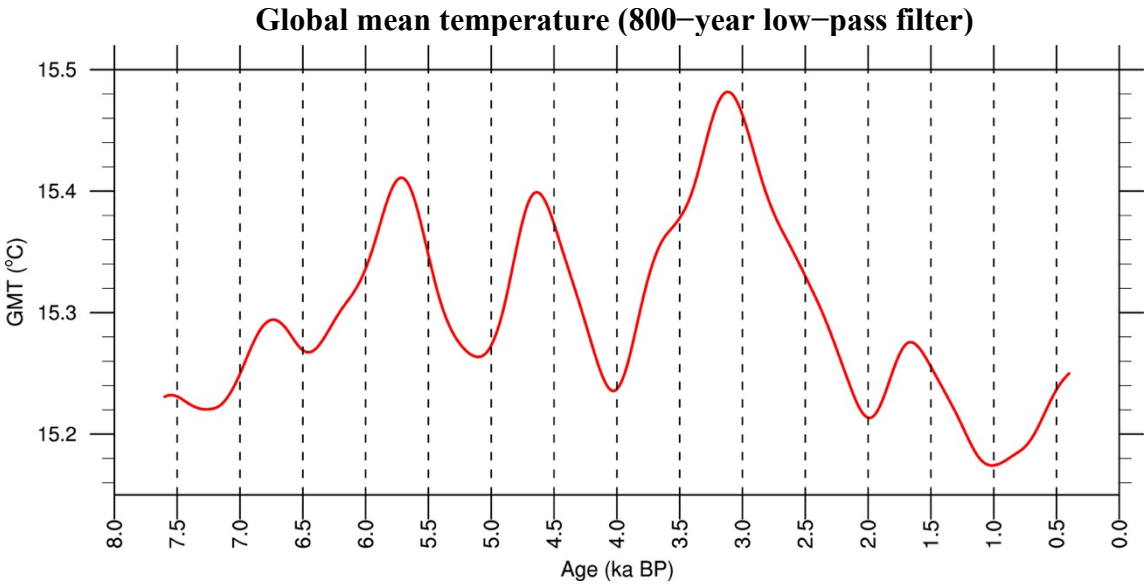

Figure 4. Global mean temperature with 800-year filter since 8k.