SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Holocene climate variability in EC-Earth3 transient simulations
Computer Project Account:	SPSEZHAN
Start Year - End Year :	2022 - 2024
Principal Investigator(s)	Qiong Zhang
Affiliation/Address:	Department of Physical Geography Stockholm University
Other Researchers (Name/Affiliation):	Zhenqian Wang Department of Physical Geography Stockholm University

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

We aimed to perform and analyze several-thousand-year-long simulations for various past climate periods using the EC-Earth3 Earth system model. Specifically, we conducted an unforced pre-industrial control simulation, and forced transient simulations for the Holocene and Last Interglacial periods. These simulations targeted understanding multi-centennial to multi-millennial climate variability. The project aimed at revealing underlying mechanisms of slow physical processes using robust statistical methods.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Initially, compilation issues arose with the LPJ component of the EC-Earth model. The departure of a key scientific programmer temporarily impacted problem-solving capabilities. However, after transitioning to the Atos system and bringing on additional research personnel, these technical issues were resolved, and no further significant problems occurred in subsequent years.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Our experience with the Special Project framework has been highly positive. The administrative aspects, including the application process and reporting requirements, were straightforward and efficient, facilitating smooth project progression and transparent resource management.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Detailed scientific results have been extensively reported in previous annual progress reports with illustrations and published in multiple peer-reviewed publications as listed. A concise synthesis of the key findings is presented below.

1. Holocene climate variability

We completed Holocene transient simulation (8000 BP to 2000 AD) with EC-Earth3, confirming significant multi-centennial climate variability. Spectral analysis revealed dominant variability periods of approximately 120-150 years, aligning well with proxy records.

We demonstrated the robustness of multi-centennial variability even without solar irradiance forcing, suggesting internal climate system mechanisms, particularly associated with the Arctic-North Atlantic region, are key drivers.

2. Mechanisms of AMOC variability

Analysis of a 3000-year pre-industrial control simulation identified a distinct multi-centennial AMOC oscillation (~200 years). Key sustaining mechanisms include salinity advection feedback, vertical mixing, and oceanic convection patterns in the North Atlantic subpolar gyre region.

This variability persisted in different forcing scenarios, emphasizing its resilience even under altered climatic conditions.

3. Multi-millennial variability and climate events

Simulations also captured prominent multi-millennial climate cycles (~1500-year period) and significant paleo-climatic events such as the 4.2k and 2.8k events, aligning with paleo-proxy records.

Further analysis is ongoing to elucidate mechanisms behind these longer-term cycles.

4. Climate feedbacks and sensitivity studies

We investigated the role of vegetation-climate feedback during the mid-Holocene and demonstrated amplified Arctic warming due to enhanced vegetation cover.

Conducted sensitivity experiments to isolate anthropogenic land-use impacts, confirming that internal variability and natural forcings drive significant multi-centennial climate variability independent of human influences.

List of publications/reports from the project with complete references

The **15** publications listed below since project year July 2022 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. **Askaer, G. T., Zhang, Q., Scheck F.**, Ljungqvist, F., et al.: Multi-centennial Holocene climate variability in proxy records and transient model simulations, manuscript to be submitted to *Quaternary Science Reivew,* 2022.
2. Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégoz, M., Miller, P. A., Moreno-Chamarro, E., Nieradzik, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., and **Zhang, Q.**: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.
3. **Chen, K., Axelsson, J., Zhang, Q.,** Li, J., and Wang, L.: EC-Earth simulations reveal enhanced inter-hemispheric ther- mal contrast during the Last Interglacial further intensified the Indian monsoon. *Geophysical Research Letters*, 49, e2021GL094551. https://doi.org/10.1029/2021GL094551, 2022.
4. Feng, R., Bhattacharya, T., Otto-Bliesner, B. L., Brady, E. C., Haywood, A. M., Tindall, J. C., Hunter, S. J., Abe-Ouchi, A., Chan, W.-L., Kageyama, M., Contoux, C., Guo, C., Li, X., Lohmann, G., Stepanek, C., Tan, N., **Zhang, Q.**, Zhang, Z., Han, Z., Williams, C. J. R., Lunt, D. J., Dowsett, H. J., Chandan, D., and Peltier, W. R.: Past terrestrial hydroclimate sensitivity controlled by Earth system feedbacks, Nature Communications, 13, 1306, 10.1038/s41467-022-28814-7, 2022.
5. Jiang, Z., Brierley, C. M., Bader, J., Braconnot, P., Erb, M., Hopcroft, P. O., Jiang, D., Jungclaus, J., Khon, V., Lohmann, G., Marti, O., Osman, M. B., Otto-Bliesner, B., Schneider, B., Shi, X., Thornalley, D. J. R., Tian, Z., and **Zhang, Q.**: No Consistent Simulated Trends in the Atlantic Meridional Overturning Circulation for the Past 6,000 Years, Geophysical Research Letters, 50, e2023GL103078, https://doi.org/10.1029/2023GL103078, 2023.
6. **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.
7. **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.
8. 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.
9. **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.
10. 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.
11. **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.
12. 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.

13. **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.
14. Lu, Z., Schultze, A., Carré, M., Brierley, C., Hopcroft, P.O., Zhao, D., Zheng, M., Braconnot, P., Yin, Q., Jungclaus, J., Shi, X., Yang, H., **Zhang, O.**: 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.
15. **Wang, Z., Zhang, Q., Chen, J., Han, Z.**: 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.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Future research will focus on detailed sensitivity analyses of individual forcing factors (e.g., volcanic activity, land-use changes, greenhouse gas concentrations) to further isolate their impacts on climate variability. We will extend our simulations to investigate dynamic vegetation feedbacks using the LPJ-GUESS module coupled with EC-Earth4, particularly focusing on the past millennium and Last Interglacial periods. Continued analysis and simulations planned for the 2025–2027 period will deepen our understanding of long-term climate dynamics and support comprehensive assessments for CMIP7 experiments.