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	12.242.966	20.000.000	23.325.000
Data storage capacity	(Gbytes)	10000	5000	50000	45000

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)

Since migrating to Atos, we have successfully resolved numerous issues, resulting in the smooth operation of our simulations as per our initial plans. However, our project entails running extensive simulations using the EC-Earth Earth system model, which necessitates significant computational resources and output storage. Unfortunately, we have already depleted the allocated computation resources for the current year, compelling us to explore alternative avenues to sustain our simulations.

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

Based on our observations of pronounced centennial variability in both our Holocene transient simulation and long PI control runs, we are conducting a series of sensitivity simulations to unravel the underlying physical mechanisms. Specifically, we are altering the CO2 concentration to investigate how different climate forcings influence low-frequency variability in the climate system. These findings have paved the way for a successful VR research proposal, focusing on exploring centennial variability using the EC-Earth model (2023-2026). In this new project, we have devised a plan to carry out five transient simulations throughout the period from 2023 to 2026. These simulations encompass two Holocene transient simulations employing varying climate forcings, a transient simulation specifically targeting glacier climates, and two equilibrium simulations for future warmer climates.

List of publications/reports from the project with complete references

The 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 results from paper 1-4 are summarized below. The name(s) from our group is in **bold**.

1. **Cao, Ni., Zhang, Q., Power, K.,** Wyser, K., and Yang, H.: On the mechanisms in sustaining multi-centennial variability of the Atlantic meridional overturning circulation in EC-Earth simulation, Earth and Planetary Science Letters, in revision, 2023.

2. **Askjaer, G. T., Zhang, Q., Scheck F.,** Ljungqvist, F., et al.: Multi-centennial Holocene climate variability in proxy records and transient model simulations, *Quaternary Science Reivew,* 296, 107801, https://doi.org/10.1016/j.quascirev.2022.107801, 2022.

3. 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.

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.

Summary of results

1. Multi-centennial climate variability

1.1 Evidence from paleo proxy data and Holocene transient simulations (Askjær et al., 2022)

We have completed a long transient simulation with EC-Earth 3.3. The Holocene transient simulation from 8000 BP until 2000 AD was finished in autumn 2022. The total simulation length is 10 000 years. The simulation results are presented in one publication to demonstrate the simulated multi-centennial climate variability (Figure 1).

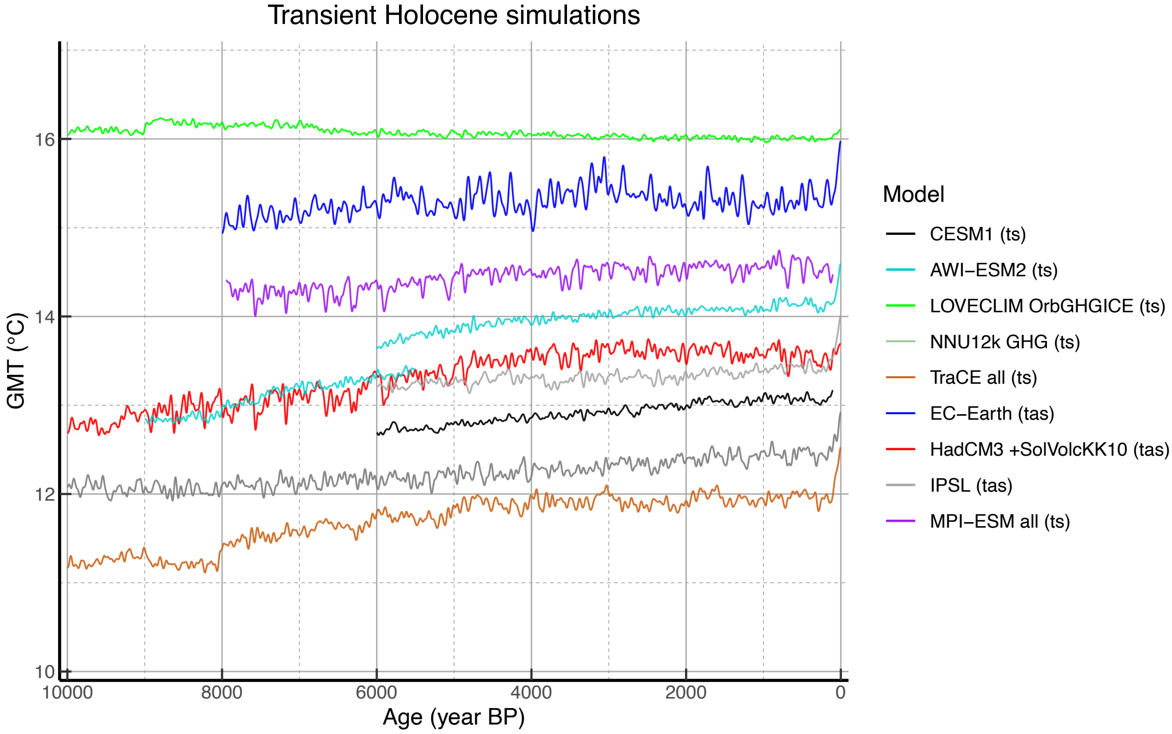

Figure 1. Global Mean Temperature time series of the full forcing transient Holocene simulations filtered with a 60-year low-pass Butterworth filter. From Askjær et al., 2022.

We conducted a spectral analysis of transient Holocene simulations from nine models (including our transient simulation with EC-Earth) and 120 proxy records to identify common signals, oscillation periods, and geographic dependencies, and to discuss potential driving mechanisms (Askjær et al., 2022).

The analysis reveals significant multi-centennial variability in most proxy records, with dominant oscillation periods around 120-130 years and an average of 240 years. The spectra of model-based global mean temperature (GMT) align well with proxy evidence, exhibiting significant multi-centennial variability across all simulations with dominant oscillation periods of approximately 120-150 years. This indicates a relatively good agreement between model and proxy data. While there is no significant latitudinal dependency observed in terms of oscillation periods in both model and proxy data, the highest spectral density in all model simulations is found in the high latitudes of the Northern hemisphere. This suggests a particular sensitivity to variability or potential driving mechanisms in this region. Differentiated forcing simulations with various combinations of forcing agents also reveal significant multi-centennial variability, including those with only orbital forcing. However, the spectral analysis does not identify a predominant driver among the different forcings.

Previous hypotheses regarding solar irradiance as the primary driver of multi-centennial variability are challenged by simulations without this forcing, which still exhibit significant multi-centennial variability. The results suggest the operation of internal mechanisms on multi-centennial timescales, with the North Atlantic-Arctic region emerging as an area of interest for further exploration.

1.2 On the mechanisms in sustaining multi-centennial variability of the Atlantic meridional overturning circulation in EC-Earth3 simulation (Cao et al., 2023)

In a pre-industrial (PI) control simulation using the EC-Earth3 climate model, a significant multi-centennial climate variability with a distinct peak at approximately 200 years is observed. This oscillation primarily originates from the North Atlantic and shows a strong association with the Atlantic Meridional Overturning Circulation (AMOC). The study identifies the interplay between salinity advection feedback and vertical mixing in the subpolar North Atlantic as key to maintaining this multi-centennial oscillation. The perturbation flow of mean subtropical-subpolar salinity gradients acts as a positive feedback, sustaining the AMOC anomaly, while mean advection of salinity anomalies and vertical mixing or convection provide negative feedback, constraining the AMOC anomaly. Notably, this low-frequency variability persists even in a warmer climate with a weakened AMOC, highlighting the robustness of the salinity advection feedback mechanism.

2. Earth system feedbacks on climate

2.1 Amplified Arc-warming due to vegetation feedback during mid-Holocene (Chen et al., 2022)

Understanding the influence of vegetation on past temperature changes in the Arctic region is crucial for reducing uncertainty and gaining a comprehensive understanding of the broader climate system. This knowledge has important implications for paleoclimate reconstructions and provides insights into future climate change. In this study, we employ the Earth system model EC-Earth to conduct a series of simulations focused on investigating the impact of vegetation-climate feedback on the Arctic climate during the mid-Holocene.

The results of our simulations reveal that Arctic greening, driven by the warming induced by stronger orbital forcing, intensifies the Arctic warming process. The presence of increased vegetation in the Arctic contributes to an additional 0.33°C of warming, accompanied by a sea ice loss of 0.35 x 10^6 km^2. This amplified warming is primarily attributed to reduced land surface albedo and increased evapotranspiration resulting from the enhanced vegetation cover, both of which contribute to local warming during the spring and summer seasons. The subsequent sea ice loss then leads to further warming in the following seasons, with additional atmospheric circulation anomalies serving to amplify the overall warming effect.

Our findings underscore the significant role played by vegetation-climate feedback in shaping the Arctic climate under natural conditions. By shedding light on the mechanisms through which vegetation impacts temperature changes, this study enhances our understanding of past climate dynamics in the Arctic and provides valuable insights for predicting future climate scenarios.

2.2 Past terrestrial hydroclimate sensitivity controlled by Earth system feedbacks (Feng et al., 2022)

Geological reconstructions of the mid-Pliocene period (3.3-3.0 million years ago) indicate significant changes in subtropical terrestrial hydroclimate, including high lake levels in the Sahel region and mesic conditions in subtropical Eurasia. While atmospheric CO2 levels (pCO2) and tectonic conditions during this period were similar to present-day, our study, utilizing a compilation of proxy data and multi-model paleoclimate simulations, reveals that these hydroclimate shifts were not driven by direct CO2 radiative forcing.

Instead, we find that the mid-Pliocene hydroclimate state was influenced by the loss of northern high-latitude ice sheets and continental greening, both of which are long-term Earth system feedbacks to elevated pCO2. These changes in ice sheet extent and vegetation cover exerted a significant influence on the hydroclimate dynamics during this period. Furthermore, we observe that the moist conditions in the Sahel and subtropical Eurasia were a result of enhanced tropospheric humidity and a stationary wave response to the surface warming pattern, which varied notably with land cover changes. This highlights the importance of land cover modifications in driving the response of subtropical hydroclimate to the mid-Pliocene warming.

Overall, our findings emphasize the potential for amplified terrestrial hydroclimate responses over long timescales to sustained CO2 forcing. By uncovering the complex interactions between ice sheet dynamics, vegetation changes, and atmospheric processes, this study enhances our understanding of past hydroclimate variations and their implications for future climate scenarios.