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	2022
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	2.205
Data storage capacity	(Gbytes)			10000	5000

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 simulation 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)

The compilation of the EC-Earth model was not success for the LPJ component, while the model works fine in supercomputer in Swedish National Computer centre. Also due to our scientific programmer left his job, we don't have manpower to investigate the problem. From July we will have a new PhD student working on this. We also try to explore Atos and hopefully can apply to our simulations.

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

We also use the HPC recourse in Swedish National Computer centre (NSC). In the first half of 2022, more recourses are available for us therefore we have performed the planned simulation mainly on NSC resources and barely used the ECMWF resource allocated to us. The situation will change from 1 July 2022 because we will have less HPC resources on NSC. We plan to run two Holocene transient simulations on ECMWF HPC resources.

List of publications/reports from the project with complete references

The publications listed below during project year July 2022 have acknowledged the HPC and data support from ECMWF. Some works may have done during the previous years. The results from paper 1-3 are summarized below. The name(s) from our group is in **bold**.

1. **Cao, Ni., Zhang, Q., Power, K.,** Wyser, K., and Yang, H.: The role of Artic Ocean in modulating the multi-centennial variability of Atlantic meridional overturning circulation, manuscript to be submitted to *Geophysical Research Letters*, 2022.
2. **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.
3. 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.
4. **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.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during**

the third project year, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

Since the simulations we produced are also used in other studies, we have acknowledged the ECMWF HPC in those publications as well (as listed publications above). Here we summarised the published results that are relevant to the Holocene climate variability in transient simulations. The report includes the mechanism study based on three long simulations with various CO2 levels, with focus on the pre-industrial climate condition (Cao et al., 2022, to be submitted to GRL), and a data-model comparison on the multi-centennial variability for the Holocene period (Askaer et al., 2022, to be submitted to QSR).

1. The role of Artic Ocean in modulating the multi-centennial variability of Atlantic meridional overturning circulation (Cao et al., 2022)

Summary. Significant multi-centennial climate variability with a clear peak at approximately 200 years is found in a pre-industrial control simulation conducted by EC-Earth3 climate model. This mainly emerges in the North Atlantic and Arctic basin and appears to be closely associated with Atlantic Meridional Overturning Circulation (AMOC). The anomalous dipole patterns of salinity and ocean currents at the Arctic and North Atlantic regions play a crucial role in modulating the multi-centennial variability of AMOC. During a lifecycle of AMOC variability, a positive (negative) feedback mechanism dominated by positive (negative) salinity anomalies in deep convection sites that are driven by strong (weak) AMOC-induced surface sea water convergence (divergence), keeps the AMOC strengthening (weakening). The fresh (salt) water accumulates in the Arctic as a result of sea-ice melting (freezing) and extends to the deep convection sites in North Atlantic to weaken (strengthen) the subpolar gyre and eventually to weaken (strengthen) the AMOC.

2. Multi-centennial Holocene climate variability in proxy records and transient model simulations (Askaer et al., 2022)

Summary: This paper presents a spectral analysis of transient Holocene simulations from 9 models and 120 proxy records with the aim of finding the general signals related to oscillation period, geographic dependencies and discuss the implications for the potential driving mechanisms. The spectral analysis of the proxy records finds multi-centennial variability significant from red noise in the majority of the proxy records, with the highest concentration of oscillation periods around 120-130 years, an average at 240, and no clear indication of it being dependent on climate variable, although temperature is the biggest group and influence the results the most. The analysis of the model global mean temperature (GMT) also finds multi-centennial variability in all simulations with the highest concentration of oscillation periods around 120-150 years and an average just slightly above that. A good agreement between model and proxy data is thereby indicated, although the spread is slightly larger for the proxy data, but this is also a more diverse collection of data than the models. A lack of latitudinal dependencies in terms of oscillation period is found in both the model and proxy data. However, all the model simulations have most spectral density distributed over the northern hemisphere high latitudes, which could indicate either a particular variability sensitivity or potential driving mechanisms in this region.

Four of the models also have differentiated forcings simulations and significant multi-centennial variability with oscillation periods between 100-200 years is found in all forcing scenarios. The simulations where only orbital forcing also show this and so the different forcings seem to induce some variability to the system, but none can be said to be the main driver based on the spectral analysis. This also includes solar irradiance, which long have been hypothesised to drive multi-centennial variability, as all the simulations without this forcing, which includes some of the full forcing simulations as well, all have significant multi-centennial variability. The results then indicate that internal mechanisms also operate on multi-centennial timescales and the Arctic is a region of interest for this aspect. The conclusions are not without uncertainties, as both proxies and model simulations have uncertainties, but when analysing with a largely uniform approach on a large data collection, there is good evidence of multi-centennial variability with oscillation periods around 100-200 years across the entire range of available Holocene paleoclimate data.