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	2020
Project Title:	Simulating the green Sahara with EC-Earth 3.2
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:	2019-01-01
Expected end date:	2021-12-31

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	14.400.389	15.000.000	495.411
Data storage capacity	(Gbytes)	5000	4000	5000	2000

Summary of project objectives (10 lines max)

We aim to run transient simulations to investigate the termination of Green Sahara. This simulation will provide a comprehensive understanding of the vegetation feedbacks in the transition phases together with the possibility of having multiple equilibria in Northern Africa. Besides the transient simulations, different sensitivity simulations will be also performed to understand the climate response and feedbacks, such as offline dynamical vegetation model simulations to determine how much precipitation would be needed to initiate a green Sahara. We also test the impact of the aerosol direct and indirect effect through a few sensitivity experiments.

Summary of problems encountered (10 lines max)

The continuous simulation has had frequent crash and it took some time to identify the problem. Since it is the first time for us to use the EC-Earth model to run several thousand years, several defined variables related to record time step has to be updated to longer length in characters. One variable ITME (integer) exceeds the limit of 10^{18}, this affects the calculation of orbital forcing that taken into account the simulation time. Now the problem is solved.

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

From 2020 to now, two transient simulations are running with EC-Earth3-veg-LR, one for Holocene transient from 8ka to 0ka (now is at 5ka), and one for last interglacial 127ka to 120ka (now is at 125k). We also have done several sensitivity experiments with the EC-Earth3-veg is performed under PI and 6ka climate condition, to test the effect of model resolution (T159 vs T255), aerosol indirect effect (to turn on/turn off first and second indirect effect) on African monsoon.

List of publications/reports from the project with complete references

The publications listed below during project year July 2020 to June 2021 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.

1. Zhang, Q., Berntell, E., Axelsson, J., Chen, J., Han, Z., de Nooijer, W., Lu, Z., Li, Q., Zhang, Q., Wyser, K., and Yang, S.: Simulating the mid-Holocene, last interglacial and mid-Pliocene climate with EC-Earth3-LR, *Geosci. Model Dev.,* 14, 1147–1169, https://doi.org/10.5194/gmd-14-1147-2021, 2021.
2. Zhang, Q., Berntell, E., Li, Q., and Ljungqvist, F. C.: Understanding the variability of the rainfall dipole in West Africa using the EC-Earth last millennium simulation, *Climate Dynamics*, 10.1007/s00382-021-05696-x, 2021.
3. Sun, W., Wang, B., Zhang, Q., Chen, D., Lu, G., and Liu, J.: Middle East climate response to the Saharan vegetation collapse during the Mid-Holocene, *Journal of Climate*, 34, 229-242, 10.1175/jcli-d-20-0317.1, 2021.
4. Zhang, Z., Li, X., Guo, C., Otterå, O. H., Nisancioglu, K. H., Tan, N., Contoux, C., Ramstein, G., Feng, R., Otto-Bliesner, B. L., Brady, E., Chandan, D., Peltier, W. R., Baatsen, M. L. J., von der Heydt, A. S., Weiffenbach, J. E., Stepanek, C., Lohmann, G., Zhang, Q., Li, Q., Chandler, M. A., Sohl, L. E., Haywood, A. M., Hunter, S. J., Tindall, J. C., Williams, C., Lunt, D. J., Chan, W.-L., and Abe-Ouchi, A.: Mid-Pliocene Atlantic Meridional Overturning Circulation simulated in PlioMIP2, *Clim. Past*, 17, 529–543, https://doi.org/10.5194/cp-17-529-2021, 2021.
5. Otto-Bliesner, B. L., Brady, E. C., Zhao, A., Brierley, C. M., Axford, Y., Capron, E., Govin, A., Hoffman, J. S., Isaacs, E., Kageyama, M., Scussolini, P., Tzedakis, P. C., Williams, C. J. R., Wolff, E., Abe-Ouchi, A., Braconnot, P., Ramos Buarque, S., Cao, J., de Vernal, A., Guarino, M. V., Guo, C., LeGrande, A. N., Lohmann, G., Meissner, K. J., Menviel, L., Morozova, P. A., Nisancioglu, K. H., O'Ishi, R., Salas y Mélia, D., Shi, X., Sicard, M., Sime, L., Stepanek, C., Tomas, R., Volodin, E., Yeung, N. K. H., Zhang, Q., Zhang, Z., and Zheng, W.: Large-scale features of Last Interglacial climate: results from evaluating the lig127k simulations for the

Coupled Model Intercomparison Project (CMIP6)–Paleoclimate Modeling Intercomparison Project (PMIP4), *Clim. Past*, 17, 63-94, 10.5194/cp-17-63-2021, 2021.
6. Piao, J., Chen, W., Chen, S., Gong, H., and Zhang, Q.: Summer Water Vapor Sources in Northeast Asia and East Siberia Revealed by a Moisture-Tracing Atmospheric Model, *Journal of Climate*, 33, 3883-3899, 10.1175/jcli-d-19-0516.1, 2020.

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 green Sahara project. The report includes the mode setup and evaluations for preforming our paleoclimate simulations in this project (Zhang et al., 2021, GMD), the western African monsoon variability during the last millennium (Zhang et al., 2021, CD), and the impact of mid-Holocene green Sahara on mid-east climate (Sun et al., 2021)

1. Simulating the mid-Holocene, last interglacial and mid-Pliocene climate with EC-Earth3-LR (Zhang et al., 2021)

Summary. Using CMIP6 version of EC-Earth3-LR, we have performed several simulations for the past climate to contribute to PMIP4/CMIP6. We have documented the model setup for these experiments and evaluated the large-scale features from the simulations. Using the pre-industrial climate as a reference state, we show global temperature changes, large-scale Hadley circulation and Walker circulation, polar warming, global monsoons and the climate variability modes. EC-Earth3-LR simulates reasonable climate responses during past warm periods, as shown in the other PMIP4-CMIP6 model ensemble. The systematic comparison of these climate changes in past three warm periods in an individual model demonstrates the model's ability to capture the climate response under different climate forcings, providing potential implications for confidence in future projections with the EC-Earth model.

2. Understanding the variability of the rainfall dipole in West Africa using the EC-Earth last millennium simulation (Zhang et al., 2021, Climate Dynamics)

Summary: In this work we investigate the rainfall variability in West Africa over longer timescales in our EC-Earth climate model simulation for last millennium (850–1850 CE). We provide the underlying physical explanation on a well-known rainfall dipole over the Sahel region and the Gulf of Guinea with statistical robust analysis. The 1000-year-long simulation data show that this rainfall dipole presents at decadal to multidecadal and centennial variability and long-term trend. Using the singular value decomposition (SVD) analysis, we identified that the rainfall dipole present in the first SVD mode with 60% explained variance associating with the variabilities in tropical Atlantic sea surface temperature (SST). The second SVD mode shows a monopole rainfall variability pattern centred over the Sahel, associated with the extra-tropical Atlantic SST variability. We conclude that the rainfall dipole-like pattern is a natural variability mode originated from the local ocean–atmosphere-land coupling in the tropical Atlantic basin. The influence from extra-tropical climate variability, such as Atlantic multidecadal oscillation, tends to modify the rainfall dipole pattern to a monopole pattern from the Gulf of Guinea to Sahara through influencing the Sahara heat low. External forcing—such as orbital forcing, solar radiation, volcanic and land-use—can amplify/dampen the dipole mode through thermal forcing and atmosphere dynamical feedback.

3. Middle East climate response to the Saharan vegetation collapse during the Mid-Holocene (Sun et al, 2021, J. Climate)

Summary: Understanding climate change in the Middle East (ME) is crucial because people's living environment depends on rain-fed crop systems. It remains unclear whether the ME climate would be affected by the Saharan vegetation collapse at the end of the mid-Holocene (MH). Proxy data suggest a transition from humid to more arid ME conditions during the period of 6.5–5 kyr BP. Using a set of idealized sensitivity experiments with an Earth system model (EC-Earth), we infer that the shift of Saharan vegetation plays a role in this wet-to-dry transition over the ME. The experimental results show that the Saharan greening can significantly increase the late winter and early spring precipitation over the ME. The reason is that the vegetation decreases the surface albedo, which induces a warming in North Africa and generation of an anomalous low-level cyclonic flow, which transports moisture from tropical North Africa and the Red Sea to the ME. The moisture also flows from the Mediterranean Sea region to the ME through the enhanced mid- to upper-level westerlies. The enhanced moisture carried by westerly and southwesterly flows is lifted upon reaching Mesopotamia and the Zagros Mountains, substantially increasing the precipitation there. When the Sahara greening is removed, a drier condition happens in the ME. The crop model simulation further shows a substantial decrease in wheat yield in Mesopotamia with the reduction of Saharan vegetation, which is consistent with paleoclimatic reconstructions. These results imply that future changes in Saharan land cover may have climatic and agricultural impacts in the Middle East.