SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Simulating the green Sahara with EC-Earth 3.2
Computer Project Account:	SPSEZHAN
Start Year - End Year :	2018-01-01—2018-12-31
Principal Investigator(s)	Qiong Zhang
Affiliation/Address:	Department of Physical Geography Stockholm University
Other Researchers (Name/Affiliation):	Qiang Li, Qiang Zhang Department of Physical Geography Stockholm University

The following should cover the entire project duration.

Summary of project objectives

The project aims to use the new CMIP6 version of EC-Earth 3.2 to run a transient simulation for mid-Holocene. We have done several experiments using the offline dynamical vegetation model. This is a sensitivity test on response of vegetation to climate. The results show that the mid-Holocene precipitation anomalies dominate the vegetation extent while temperature anomalies adjust the vegetation composition. These sensitivity experiments confirm that dynamical vegetation model LPJ-GUESS has the potential to simulate realistic vegetation during past African humid periods when coupled to EC-Earth. We further setup the fully coupled Atmosphere-Ocean-Land and vegetation model and did the test run. The simulation is still running. Another test with offline TM5 is ongoing to test the contribution of dust.

Summary of problems encountered

We are responsible for the model tunning of low-resolution (T159 for atmosphere and land model) version of EC-Earth, but the tunning results are not satisfactory. We further collaborate with the colleagues in SMHI for this tunning effort. Before the T159 is well tunned, some fully coupled simulations are run with well tunned T255 version. For the planned long transient simulation, we will stick to the T159 version.

Experience with the Special Project framework

The experiences with application procedure and progress report are very good, I highly appreciate the remind sent from the system or administrative for the submission. Progress report is a nice way for us to check on the usage of the resources and to make better plan for the future work. We also use the opportunity of annual EC-Earth meeting held in ECMWF and communicate with the other resource users, to learn how to efficiently use the HPC.

Summary of results

Within the Green Sahara project that funded by the Swedish Research Council, we have established national/international collaboration in EC-Earth community, and with MPI-ESM model group. Aim to understand the climate-vegetation-aerosol interaction in the climate system. Each group contribute with their expertise, for instance, the modelling group in Lund University have been contributing to couple the dynamical vegetation model LPJ-Guess with EC-Earth. And the modelling group in Helsinki University contribute the aerosol component in TM5 module. We also have had MPI group where they have been working on the green Sahara topic for many years, to gain the knowledge from their experiences.

1. Simulating the Green Sahara using the dynamic vegetation model LPJ-GUESS

To qualitatively evaluate such hypotheses of the orbital-climatic causation of the green Sahara regime, we performed simulations with a dynamic vegetation model, LPJ-GUESS, driven by climate forcings from mid-Holocene time-slice simulations with a coupled model EC-Earth, in which the vegetation is either prescribed to be modern desert or artificially vegetated with reduced dust load. LPJ-GUESS simulates a vegetated Sahara covered by both herbaceous and woody vegetation types consistent with proxy reconstructions only in the latter scenario. This northward expansion of vegetation is associated with a substantially intensified West African monsoon. Sensitivity experiments further suggest that the increased precipitation is the main driver of the change, and the temperature anomalies adjust the plant functional types by fire disturbance. These offline LPJ-GUESS simulations provide constraints on the simulated mid-Holocene vegetation in coupled earth system model studies with EC-Earth in the CMIP6-PMIP4 framework.

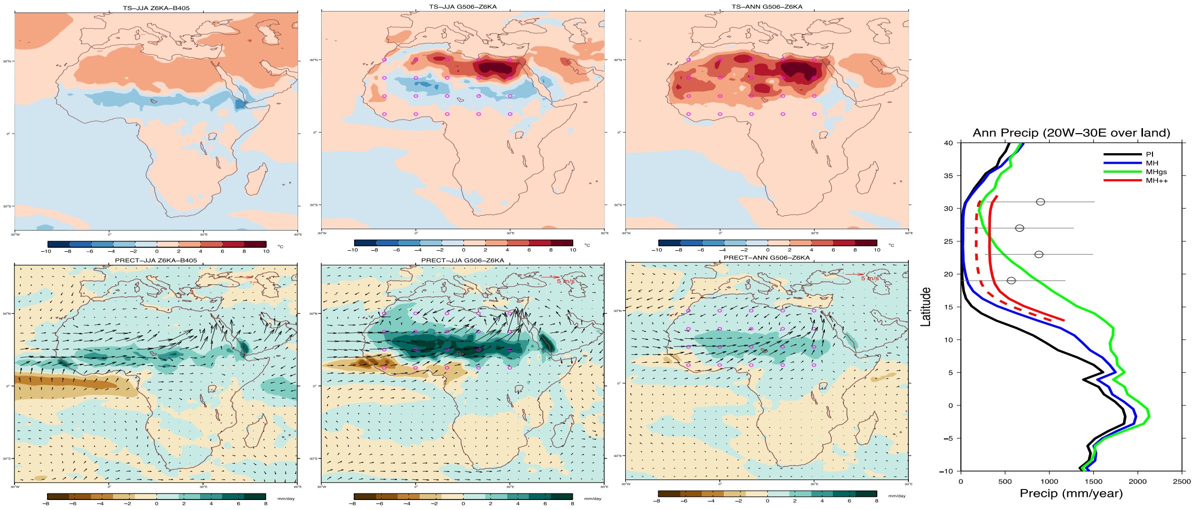

Figure 1. Climate forcing (surface air temperature, total precipitation and 925hPa wind) anomalies from EC-Earth for MH minus PI (a,b) and MH_gsrd minus MH (c-f). (g) Zonal mean (20W-30E over land) annual precipitation. Purple circles in (c-f) depict the 4X5 individual grid cells in the following analyses.

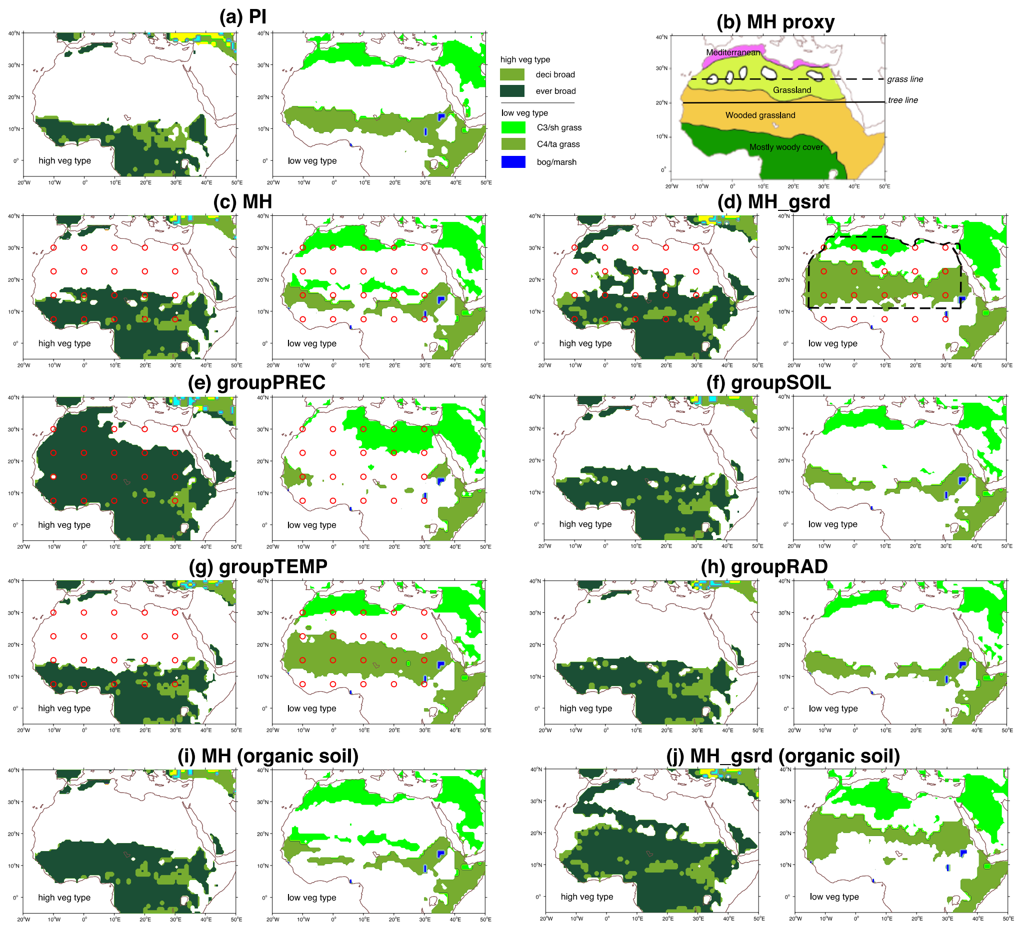

Figure 2. Simulated (a, c-j) vegetation types, in each panel high vegetation is on the left and low vegetation is on the right. Bare soil is set where vegetation cover is less than 20%. Red circles in (c,d) depict the 4X5 individual grid cells in the following analyses. (b) Reconstructed vegetation types from Larrasonana et al. (2013), and black solid line and dashed line show reconstructed tree line and grass line (Hely et al., 2014).

We take the climate forcing from the previous EC-Earth Green Sahara simulations to drive the LPJ-GUESS (Fig 1), considering a standard mid-Holocene run and an imposed green Sahara run. The spatial distribution of vegetation simulated with forcing from each of the GCM experiments was compared using 20-year averaged vegetation maps after model equilibrium. Only a slight northward expansion of vegetation was simulated by LPJ-GUESS in the MH forcing experiment (MH) compared to the PI forcing simulation (PI). The high vegetation, mainly consisting of evergreen broadleaf trees, migrated northward by ~5-degree latitude (Fig. 2c). The slightly short grasses emerge to the north of the tree line (Fig. 2c). In the MH_gsrd forcing simulation (MH_gsrd), the vegetation is extended considerably further northward, with tall grasses as far north as 30N (Fig. 2d) along with scattered woody vegetation (Fig. 2d). The MH_gsrd vegetation is qualitatively consistent with recent vegetation/hydrological reconstructions, in which the wooded grassland and grassland is reported as reaching as far north as 22-23°N and 26-27°N, respectively (Fig. 2b) during the mid-Holocene.

The driving mechanisms of the simulated vegetation patterns were investigated by additional simulations. These simulations focus on the effect of individual forcing changes (from MH to MH_gsrd) in precipitation, air temperature, soil properties and surface radiation, respectively. In groupPREC, the vegetation response is the greatest—almost cover the whole of North Africa (Fig. 2e). It is characterized by the large area of high vegetation, mostly temperate broadleaved evergreen trees, and to the northeast are denser C3 grasses. In contrast, in groupTEMP the extension of the high vegetation is more limited, while the low vegetation as represented by C4 grasses is found further north, comparable to that seen in MH_gsrd. Both high and low vegetation in groupSOIL and groupRAD are quite similar to those in MH (Fig. 2c,g,h), which implies their minor direct impacts on the simulated 'Green Sahara'.

The above modeling results using LPJ-GUESS provide a basis for improved understanding of the 'Green Sahara' biosphere response to climate forcings in the CMIP6-PMIP4 framework. LPJ-GUESS, forced by atmospheric fields generated by an idealized EC-Earth MH_gsrd simulation, is able to reproduce the mid-Holocene vegetation cover in Sahara region in reasonable agreement with reconstructions. Changes to the vegetation extent can be mainly attributed to precipitation anomalies, and changes to the vegetation composition can be mainly attributed to the temperature anomalies in combination with fire interactions. The radiation and soil temperature/moisture forcing have limited impacts on vegetation.

Our modeling results agree reasonably well with proxy reconstructions and other DGVM simulations. The potential model bias in soil texture is quantified, and has a moderate influence on vegetation composition, with organic soils favoring high vegetation in the wetter MH conditions. They provide upper and lower limits on the simulated mid-Holocene vegetation in future coupled ESM studies.

This work represents a step towards carrying out fully-interactive multi-millennial simulations using the coupled Earth system model (ESM) framework EC-Earth-LPJ-GUESS. Mid-Holocene simulations with this framework will aim to capture the vegetation-climate feedbacks believed to be associated with the observed transitions into and out of the Green Sahara period. These vegetation feedbacks will be examined in the future using fully-coupled ESM simulations of the paleoclimate transition in North Africa.

2. A dipole rainfall mode in western Africa during last millennium

A 1000 years long simulation with EC-Earth3.1 from 850 to 1850 CE enable us to investigate the internal and forced climate variability over western African. Our model results show a common variability feature exhibit in all time scales, that is, a diploe pattern between the subtropical Sahel region and tropical Coast of Guinea (Fig.3). This includes an overall drying trend during last millennium, characterized with wet condition during the Medieval Warm Period and dry condition during Little Ice Age. By removing the linear trend caused by external forcing, we found that high decadal variability in rainfall over the Coast of Guinea, which is modulated by the tropical Atlantic SST. While the rainfall variability over the Sahel region exhibits strong multidecadal variability, which is closely connected to Atlantic multidecadal variability (Fig.4). This work shows that the dipole is an intrinsic climate variability pattern, it is modulated by the SST in Atlantic, the external forcing during the last millennium such as solar radiation and volcanic eruptions can enhance/weaken the rainfall variability (Zhang et al., in preparation).

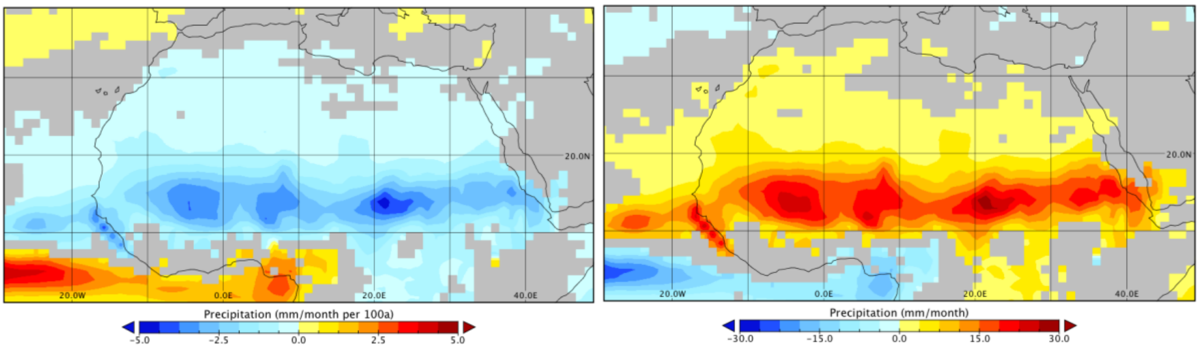

Figure 3. The linear trend (JAS mean) over northern Africa regionfor JAS mean precipitation (left, unit: mm/month); and the change in JAS rainfall (right, unit: mm/month) between Medial Warm Period (MWP, averaged for 900-1200 CE) and Little Ice Age (LIA, averaged for 1550-1850 CE).

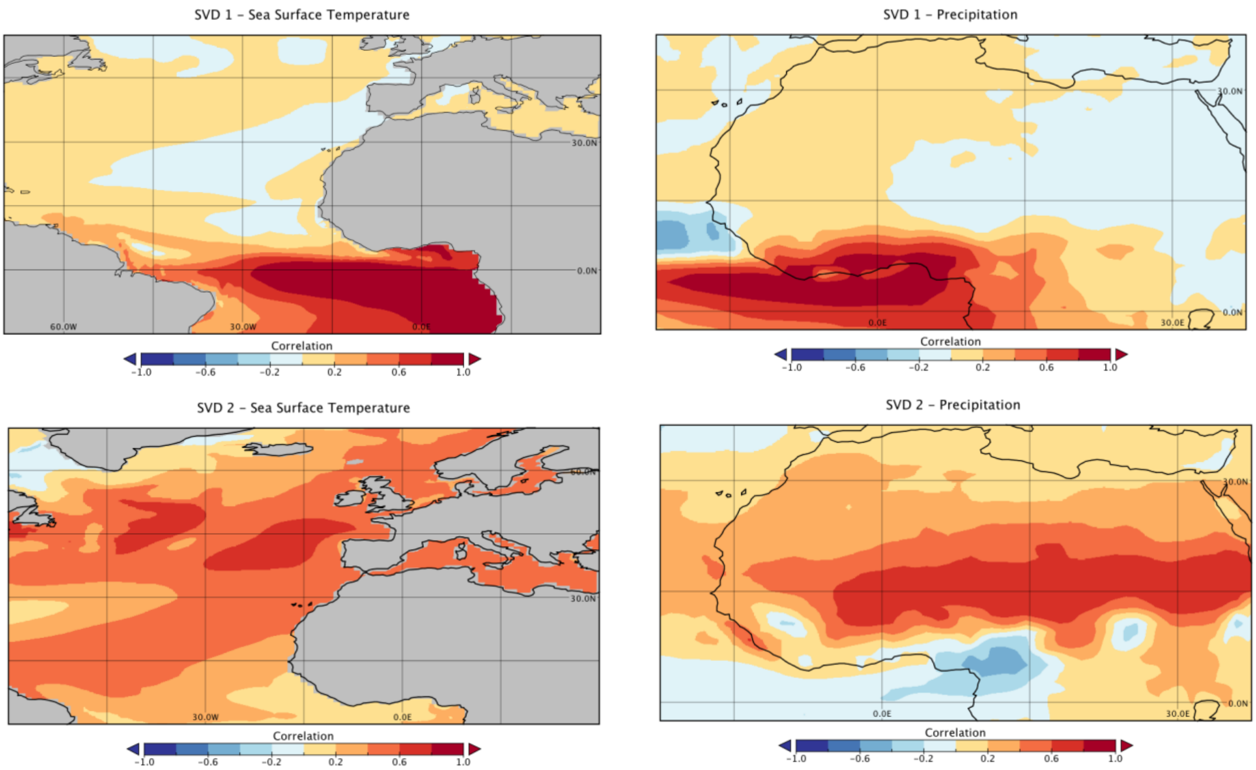

Figure 4. The first and second leading SVD in heterogeneous correlation map for SST mode 1 and 2 (left) and rainfall mode 1 and 2 (right).

List of publications/reports from the project with complete references

The publications listed below during 2018-2019 have acknowledged the HPC and data support from ECMWF. Some works may have done during the previous years.

Ljungqvist, F. C., Q. Zhang, G. Brattström, P. J. Krusic, A. Seim, Q. Li, Q. Zhang and A. Moberg, 2019: Centennial-scale temperature change in last millennium simulations and proxy-based reconstructions. Journal of Climate. https://doi.org/10.1175/JCLI-D-18-0525.1.

Messori, G., M. Gaetani, Q. Zhang, Q. Zhang and F. S. R. Pausata, 2019: The water cycle of the mid-Holocene West African monsoon: The role of vegetation and dust emission changes. *International Journal of Climatology*, **39**(4): 1927-1939.

Zheng, J., Q. Zhang, Q. Li, Q. Zhang, and M. Cai, 2019: Contribution of sea ice albedo and insulation effects to Arctic amplification in the EC-Earth Pliocene simulation, *Clim. Past*, 15, 291-305, https://doi.org/10.5194/cp-15-291-2019.

Lu, Z., P. A. Miller, Q. Zhang, Q. Zhang, D. Wårlind, L. Nieradzik, J. Sjolte, and B. Smith, 2018: Dynamic vegetation simulations of the mid-Holocene Green Sahara. *Geophysical research letters, 45*. https://doi.org/10.1029/2018GL079195.

Berntell, E., Q. Zhang, L. Chafik, H. Körnich, 2018: Representation of multidecadal Sahel rainfall variability in 20th century reanalyses. *Scientific Reports,* 8:10937, DOI:10.1038/s41598-018-29217-9.

Lavender, S. L., K. J. E. Walsh, L.-P. Caron, M. King, S. Monkiewicz, M. Guishard, Q. Zhang, and B. Hunt, 2018: Estimation of the maximum annual number of North Atlantic tropical cyclones using climate models. *Science Advances,* **4**.

Piao, J., W. Chen, Q. Zhang, and P. Hu, 2018: Comparison of moisture transport between Siberia and Northeast Asia on annual and interannual time scales. *Journal of climate*, 31(18):7645-7660.

Future plans

We will continue the planed work on Green Sahara by using fully coupled EC-Earth-LPJ-GUESS. The coupled version has been tested and in running now. We have been granted a new SP project on this project and will continue to perform the mid-Holocene transient simulation. Launch of the new simulation is in progressing now with a first version that includes the dynamical vegetation.

Within the collaboration in EC-Earth community, the planned interactive dust is also progressing well in Helsinki group with offline test first. We expect to launch a second transient Holocene run when an interactive aerosol module is possible.