REQUEST FOR A SPECIAL PROJECT 2019–2021

MEMBER STATE: Sweden

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Project Title: Simulating the green Sahara with EC-Earth 3.2

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If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP**SEZHAN	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2019	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2019-2021: (To make changes to an existing project please submit an amended version of the original form.)		**2019**	**2020**	**2021**
High Performance Computing Facility	(SBU)	15.000.000	20.000.000	15.000.000
Accumulated data storage (total archive volume)[2]	(GB)	5000	5000	5000

An electronic copy of this form must be sent via e-mail to: *special_projects@ecmwf.int*

Electronic copy of the form sent on (please specify date):

June 26, 2018

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide an annual progress report of the project's activities, etc.

[2] If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year.

Principal Investigator: Qiong Zhang

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Extended abstract

Within a project "Simulating the green Sahara with Earth System Model" funded by Swedish Research Council for 2018-2021, we plan to use EC-Earth 3.2 to run a few thousand years transient simulation in mid-Holocene. A similar proposal has been submitted to ECMWF in 2017 for model tunning and testing in 2018. A progress report has been submitted for these progresses. We will continue the planned simulations in this project and therefore need the computation support from ECMWF for another three years. The scientific background, motivation, questions and simulation plan are described below.

Background and aims

What is now the world's largest Sahara Desert was the home to hunter-gatherers who made their living off the animals and plants that lived in the region's savannahs and wooded grasslands some 5,000 to 11,000 years ago (Hoelzmann et al. 1998) (Fig 1a). The North Africa received more rainfall and was about 10 times as wet as today, leading to higher level of lakes (Tierney et al. 2011) as shown in Figure 1b, and the vegetated area extended as far north as 31°N (Tierney and Pausata 2017), thus created a "Green Sahara". The period is also called "African Humid Period". The Green Sahara was a direct result of African monsoonal climate responses to periodic variations in the Earth's orbit around the Sun.

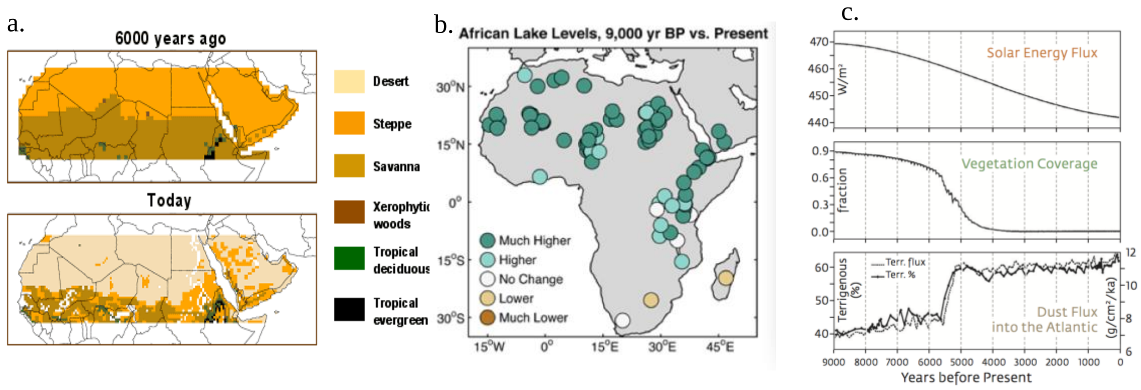

Figure 1. Contrast of vegetation coverage and types (a, (Hoelzmann et al. 1998) and lake levels (b, Tierney, et al., 2011) during 9-6 thousand years ago and today. In (c) shows the changes in summer (June to August) insolation and dust flux into Atlantic (deMenocal et al. 2000).

The Sahara Desert is also known as the planet's largest source of dust, so one can image that a Green Sahara would produce much less dust. A dust record from the Atlantic (deMenocal et al. 2000) suggests that dust emissions over the vegetated Sahara were 70 to 80% lower during mid-Holocene (about 6000 years ago) than today. More interestingly, it also shows that the beginning and termination of the Green Sahara period were abrupt, occurring within decades to centuries (Fig 1c). This feature, an abrupt change of Africa climate-ecosystem, motivated a series of Holocene climate simulations that attempted to reproduce the abrupt transition explicitly and explain underlying mechanisms (Claussen et al. 1999; Liu et al. 2007; Rachmayani et al. 2015; Renssen et al. 2003). These studies have had different explanations for the abrupt change, but all involve the interaction between the climate and vegetation. The rapid development of climate models towards Earth System Models (ESM) with the coupling of climate and ecosystems now provides us the opportunity to further investigate these fascinating events happened in the past and to improve our scientific understanding on environmental and climate change.

Observations show that under current global warming the Sahel region has experienced a rainfall recovery since 1980 after a 30-year persistent drought (Dong and Sutton 2015) and the region is greening due to development of farming and effects of CO_2 fertilization (Zhu et al. 2016). Although these ongoing changes in climate and ecosystem have much smaller amplitude compared with the dramatic regime shift seen during mid-Holocene, these changes might be amplified to some extent due to ecosystem feedbacks to climate. Therefore, the assessing and improving the ability of an ESM to represent the interactions within ecosystems in this area and climate will improve its reliability to the ESM in future projection.

Scientific question and hypotheses

Within this project we will explore the mechanisms of abrupt transition from Green Sahara to Desert Sahara. The best evidence for an abrupt termination of Green Sahara comes from a dust record located off the coast of Mauritania (deMenocal et al., 2000). There are other evidences show this abrupt change, such as sharply fell of lake levels (Street and Grove 1979; Tierney et al. 2011), a rapid retreat of mesic taxa in fossil pollen records from African lake basins (Lézine and Hooghiemstra 1990; Lézine and Casanova 1991). This sudden change in the climate, ecosystem and lakes in Sahara and Sahel has been difficult to explain and climate models are then used to test the different hypothesis.

Climate-vegetation feedback

One hypothesis suggests that the interactions between the atmosphere and vegetation cover of the region may produce this nonlinear behaviour. Several model studies have demonstrated how changes in monsoon rainfall of northern Africa might have been amplified through feedbacks from the expanded vegetation cover (Braconnot et al. 1999; Claussen and Gayler 1997; Kutzbach et al. 1996; Texier et al. 2000). Climate models have shown that multiple equilibria in the climate-terrestrial ecosystem can coexist under the same precessional forcing over northern Africa (Wang and Eltahir 2000; Zeng and Neelin 2000). In the theory of dynamic systems, these multiple equilibria would imply possible abrupt changes of the coupled system under a gradual forcing.

Nonlinear response of the vegetation to a rainfall threshold

With a synchronously coupled atmosphere-ocean-vegetation model, Liu et al. (2007) suggests a new mechanism for the abrupt desertification during mid-Holocene. Their 6500 years transient simulation has shown that the abrupt change is induced by low frequency climate variability, rather than a strong vegetation feedback and the associated multiple equilibrium. Their model simulated the major abrupt vegetation collapse in the southern Sahara at about 5000 years ago. However, the local rainfall shows a much more gradual decline with time, implying a lack of strong positive vegetation feedback on annual rainfall during the collapse. The vegetation change in Sahara is driven by local rainfall decline and strong rainfall variability. In contrast, the change of rainfall is dominated by internal climate variability and a gradual monsoonal response to orbital forcing.

These previous modeling studies on the abrupt transition from Green Sahara to Desert Sahara proposed strong nonlinearity in the interaction between different components in climate system and ecosystem. Now more physical processes as well as interaction and feedback between climate and vegetation and dust are included in ESM. This provides us with the new opportunity to simulate the regime transition of Green Sahara and understand the mechanisms. Giving the fact of that the earth has been greening in the past three decades (Zhu et al., 2016), a better understanding of such nonlinearity in the coupled ESM would inform us if such abrupt change can happen in near future.

Implications for future climate change: will Sahara become green again?

Petit-Marie hypothesized in 1990 that increase in atmospheric CO_2 concentration would lead to a warmer climate that in some respect could resemble the Holocene climate optimum with its greener Sahara. Today's satellite data does show CO_2 fertilization effects lead to greening trends in the tropics (Zhu et al. 2016) and Sahel is among the largest greening region. Meanwhile, metrological observations show the Sahel rainfall recovery in the past three decades (Dong and Sutton 2015), suggests that the much smaller but still substantial changes in greenhouse gases over recent decades nevertheless seem to have been large enough to control the evolution of western African monsoon. Looking forward to the next few decades, greenhouse gas concentrations will continue to rise. This rise is favourable for sustaining, and potentially amplifying, the recovery of Sahel rainfall and greening of Sahel. The positive feedback between rainfall and vegetable will further amplify the monsoon and possibly lead to a northward shift of monsoon and extension of greening to Sahara.

EC-Earth 3.2 and the dynamic vegetation-terrestrial ecosystem model LPJ-GUESS

We will use EC-Earth 3.2 in this project. EC-Earth is developed by a consortium of European research institutions, to build a fully coupled Atmosphere-Ocean-Land-Biosphere ESM usable for both seasonal to decadal climate prediction and for climate projections (Hazeleger et al. 2010). The atmospheric component of EC-Earth is based on Integrated Forecasting System (IFS) including a land model H-TESSEL, which is developed at the European Centre for Medium-Range Weather Forecasts (ECMWF). The ocean component is based on Nucleus for European Modelling of the Ocean (NEMO) (Madec 2008), and includes a sea-ice model LIM3 (Bouillon et al., 2009). We will use the low-resolution version EC-Earth-LR, in which the atmosphere component IFS has a T159 horizontal spectral resolution (roughly 1.125° ~ 125 km) with 62 vertical levels. The ocean component NEMO has a nominal horizontal resolution of 1° and 75 vertical levels.

We will run the EC-Earth in coupled mode with the state-of-the-art dynamic vegetation and ecosystem model Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) (Smith et al. 2001; Smith et al. 2014). LPJ-GUESS is a process-based model of vegetation dynamics and biogeochemistry that incorporates a detailed, individual- and patch-based representation of vegetation structure and dynamics.

Model simulation plan

We will setup the transient simulations to investigate the termination of Green Sahara. The planned transient simulation will be about 3,000 years long from 7,500 BP to 4,500 BP. 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.

We have already implemented the orbital forcing into EC-Earth, therefore the orbital forcing will be internally calculated in the model. The vegetation properties will be updated dynamically by LPJ-GUESS, in response to observed greenhouse gas (CO_2) forcing and the climate generated by IFS in response to orbital forcing and the same CO_2 time series. We will develop a dust reconstruction based on the proxy data available (Adkins et al. 2006; deMenocal et al. 2000). Alternatively, we will turn on the interactive dust EC-earth TM5 component, through close collaboration with Finnish group.

Justification of the computing resources

This research project from Swedish Research Council for four years 2018-2021. Our aim is to carry out a transient simulation for 3000 years within the project, plus several sensitivities runs. Before launching the transient simulation, an equilibrium run using the atmosphere-ocean coupled version needs to be done and this is expected to be at least 500 model years long. In the latest test for EC-Earth v3.2, we used 108 cores for IFS and 180 cores for NEMO, 1 core for XIOS and 1 core for RUNOFF, in total of 290 cores for the coupled model. It cost 8000 SBU for one model year simulation. The total cost will be 45 million SBU, we request 15 million SBU each year and will apply for other computing resources e.g. at National Supercomputer Center in Sweden. The amount of output data for one model year is 30G, we will process the output to monthly mean data and transfer the processed data to local storage in Sweden, we apply 5T storage every year.

As reported in the progress report, the long transient simulation demand huge computation, while with such a heavy earth system model EC-Earth, with the low resolution T159, approximately we can run10 simulation years per day (SYPD). It indicates that a planned 3500 years simulation will need more than one year to complete. From second half of 2019 we have finished the setup and enter the production stage, we would like to request 5,000,000 SBU more for 2020, that will increase the granted 15,000,000 SBU to 20,000,000 SBU. The need for 2021 will be according to the simulation progress and report in 2020.

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