Quaternary Science Reviews 125 (2015) 91–97

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Arctic climate response to the termination of the African Humid Period

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A R T I C L E I N F O

Article history:
Received 22 November 2014
Received in revised form
30 July 2015
Accepted 7 August 2015
Available online 22 August 2015

Keywords:
Mid Holocene
African Humid period
Arctic climate
Atmospheric circulation

A B S T R A C T

The Earth's climate response to the rapid vegetation collapse at the termination of the African Humid Period (AHP) (5.5–5.0 kyr BP) is still lacking a comprehensive investigation. Here we discuss the sensitivity of mid-Holocene Arctic climate to changes in albedo brought by a rapid desertification of the Sahara. By comparing a network of surface temperature reconstructions with output from a coupled global climate model, we find that, through a system of land-atmosphere feedbacks, the end of the AHP reduced the atmospheric and oceanic poleward heat transport from tropical to high northern latitudes. This entails a general weakening of the mid-latitude Westerlies, which results in a shift towards cooling over the Arctic and North Atlantic regions, and a change from positive to negative Arctic Oscillation-like conditions. This mechanism would explain the sign of rapid hydro-climatic perturbations recorded in several reconstructions from high northern latitudes at 5.5–5.0 kyr BP, suggesting that these regions are sensitive to changes in Saharan land cover during the present interglacial. This is central in the debate surrounding Arctic climate amplification and future projections for subtropical precipitation changes.

1. Introduction

The Mid Holocene is a critical period of climate change for the present interglacial. This transitional phase is characterised by a change in the boundary conditions of the Earth's climate system when the Laurentide and Eurasian ice-sheets had largely vanished, sea-level rise stabilized, and meltwater fluxes became negligible (Debret et al., 2009). Studies on climate cycle periodicities highlight a prominent global discontinuity of periodic modes at 5.5–5.0 kyr BP, suggesting a variation in the regional interplay between atmosphere, ocean, ice, and vegetation (Wirtz et al., 2010). This shift corresponds to a rapid climate oscillation that marks in several reconstructions the inception of a pervasive climate reversal, representing the transition into the Neoglacial cooling, which encompasses major changes of the dominant hydro-climate regimes (Magny and Haas, 2004) and a substantial reorganization of the North Atlantic circulation pattern (Sorrel et al., 2012). Prime candidates for direct forcing upon this widespread climate shift are a combination of changes in orbital configuration and solar activity minima (Magny and Haas, 2004). However, a comprehensive understanding of the triggering mechanism of the mid-Holocene climate changes remains elusive and owing to difficulties with dating accuracy it is problematic to evaluate precisely the contribution of high versus low latitudes.

An overlooked factor for large-scale amplification of climate change during the Mid Holocene is the rapid desertification of the Sahara that is evident in many proxy records, also known as the termination of the African Humid Period (AHP). In fact, reconstructions from both marine and terrestrial environments (deMenocal et al., 2000; Gasse, 2001; Kuhlmann et al., 2004; McGee et al., 2013; Tierney and deMenocal, 2013; Armitage et al., 2015), together with archaeological evidence (Kuper and Kröpelin, 2006; Manning and Timpson, 2014), suggest that subtropical North Africa underwent a widespread vegetation collapse and desertification of the Saharan region at 5.5–5.0 kyr BP, which took place within a few centuries (Tierney and deMenocal, 2013; Shanahan et al., 2015). The abruptness of the vegetation decline

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http://dx.doi.org/10.1016/j.quascirev.2015.08.012
0277-3791/

can be explained mainly in terms of internal, regional dynamics of the climate system resulting either from a non-linear, biogeophysical feedback of the vegetation to the gradual decrease in orbital monsoonal forcing (Claussen et al., 1999; Zhao et al., 2007), or from an intrinsic threshold behaviour of the subtropical hydrological system (Liu et al., 2006). New evidence indicates that a weakening of the African monsoon system during interglacial periods can occur independently from high-latitude forcing (Gibson and Peterson, 2014). Hence, the Sahara can be considered as a potentially critical component of the Earth's climate system (Patricola and Cook, 2008), which could have produced abrupt large-scale climate change during the Mid Holocene through changes in surface albedo and regional temperatures.

To test the sensitivity of the large-scale climate system to the rapid mid-Holocene change in Saharan vegetation cover, we combined a data set of surface temperature reconstructions and output from state-of-the-art global ocean-atmosphere climate model EC-Earth. Specifically, we used proxy records to estimate temperature anomalies across the transition from a vegetated state of the Sahara into more arid conditions, and compared the proxy data with results from two highly idealized sensitivity experiments representing a green Sahara and a desert Sahara. We emphasize that, given the fragmentary knowledge on the mid-Holocene distribution of vegetation over the Sahara, these simulations are not intended to realistically reproduce changes in the spatial extent of vegetation. Rather, the simulated scenarios are used to explore the mechanisms underlying rapid changes in subtropical land cover and to put the results in the context of the atmosphere-ocean circulation shifts recorded in several high-latitude climate reconstructions at 5.5–5.0 kyr BP.

2. Methods

2.1. Proxy data

Quantitative paleoclimatic reconstructions used for the proxy-model data comparison were systematically selected from a newly published and exhaustive database of Arctic Holocene proxy climate records (Sundqvist et al., 2014). Regrettably, yet there are no quantitative paleoclimatic records from the Sahara. Therefore, a direct comparison between reconstructions and model output data was not possible for this sector. Individual paleoclimate records were critically evaluated prior to inclusion in the database according to the following criteria: *i*) records are located north of 58°N; *ii*) the proxy records have a demonstrated relation with surface temperatures; *iii*) time-series are continuous and include (at minimum) the entire 6.0 to 2.0 kyr BP interval; *iv*) records are resolved at sub-millennial scale; *v*) records are constrained by at least one chronological data point every 3000 years back to 6.0 kyr BP; *vi*) all records and paleoclimate estimates were published in the peer-reviewed literature.

To assess the performance of our simulations, we decided to further circumscribe the number of proxy records by imposing strict chronological and resolution criteria. We narrowed down the selection of the temperature records to reconstructions that presented age sample resolutions higher than 250 years and geochronology accuracy scores higher than 0 as described in Sundqvist et al. (2014). Thus, we identified in total 46 temperature proxy reconstructions. A full list of sites and records used in this study is presented in Supplementary Table S1.

Our goal is to compare the simulated desert and green Sahara conditions with proxy data evidence after and before the mid-Holocene desertification of the Sahara, which occurred at 5.3 ± 0.3 yr BP according to the most accurate chronologies (Garcin et al., 2012). We thus defined two reference periods for which we calculate the temperature change recorded in the proxy records. The two periods were defined as the 1000-years intervals centred on 6.0 kyr and 5.0 kyr BP, respectively. We consider this as a suitable temporal framework for comparison with the simulations, encompassing the transition from a vegetated state of the Sahara into more arid conditions. We are aware that the upper reference interval is relatively too old with respect to the age for termination of the AHP, but this enables us to avoid the influence from negative temperature anomalies associated with the 4.2 kyr BP cold event (e.g. Bond et al., 2001), which might add substantial biases on our calculations. Hence, it should be born in mind that the climate anomalies presented here are a conservative estimate of the climate change at the transition out of the AHP.

It seems prudent to assume that 1000-years time windows should provide a meaningful quantification of climate change between the two periods, minimizing the possible effects from internal high-frequency climate variability. We thus averaged the reconstructed temperature data over the 1000-years windows defined as 6.0 ± 0.5 kyr BP and 5.0 ± 0.5 kyr BP, respectively. However, three proxy series did not extend up to 6.5 kyr BP. We therefore defined a different lower time window for these series, i.e. 5.75 ± 0.25 kyr BP.

All non-annual time-series were linearly interpolated to 10-years resolution before calculating the 1000-years averages. Temperature anomalies between the two reference periods were then estimated subtracting the 1000-years mean at 6.0 kyr BP from the mean at 5.0 kyr BP ($\Delta T_{5kyr-6kyr}$). In addition, we calculated the statistical significance associated with the anomalies using a Bayesian estimation test, which provides a probability distribution over the difference between two sample populations (Kruschke, 2013).

2.2. EC-Earth model description and experiment setup

The global climate model EC-Earth was used to undertake the two sensitivity experiments in the present study. EC-Earth is developed by a consortium of European research institutions, which collaborate in the development of a new Earth System Model (ESM). The goal of EC-Earth is to build a fully coupled Atmosphere-Ocean-Land-Biosphere model usable from seasonal to decadal climate prediction and climate projections (Hazeleger et al., 2010). The atmospheric component of EC-Earth is based on the modelling systems, i.e. Integrated Forecasting System (IFS), which is developed at the European Centre for Medium-Range Weather Forecasts (ECMWF), and the ocean component is based on Nucleus for European Modelling of the Ocean (NEMO) (Madec, 2008), including a sea-ice model LIM3 (Bouillon et al., 2009). The ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler (Valcke, 2006).

A number of model integrations such as historic simulations (e.g. 1850 to 2005 with known climate forcing such as greenhouse gas, volcanic, aerosol etc.) and scenarios of future possible climates taking into account an increased amount of greenhouse gases (e.g., RCP45, RCP85 etc.) have been conducted using EC-Earth version 2.3. These results contribute to the CMIP5 (Climate Model Intercomparison Project Phase 5) experiments, which form an essential part of the IPCC Fifth Assessment Report. An evaluation of EC-Earth for the Arctic shows that the model simulates the 20th century Arctic climate reasonably well (Koenigk et al., 2013). However, sea-ice thickness and extent are overestimated compared to observations and reanalyses. EC-Earth is also used for past climate studies. For instance, the effect of mid-Holocene orbital forcing on summer monsoons is investigated with EC-Earth 2.3 (Bosmans et al., 2011) and results confirm the findings from proxy data on the monsoon behaviour during this period.