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Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period

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ABSTRACT

The West African Monsoon (WAM) is crucial for the socio-economic stability of millions of people living in the Sahel. Severe droughts have ravaged the region in the last three decades of the 20th century, highlighting the need for a better understanding of the WAM dynamics. One of the most dramatic changes in the West African Monsoon (WAM) occurred between 15000–5000 yr BP, when increased summer rainfall led to the so-called "Green Sahara" and to a reduction in dust emissions from the region. However, model experiments are unable to fully reproduce the intensification and geographical expansion of the WAM during this period, even when vegetation over the Sahara is considered. Here, we use a fully coupled simulation for 6000 yr BP (Mid-Holocene) in which prescribed Saharan vegetation and dust concentrations are changed in turn. A closer agreement with proxy records is obtained only when both the Saharan vegetation changes and dust decrease are taken into account. The dust reduction strengthens the vegetation–albedo feedback, extending the monsoon's northern limit approximately 500 km further than the vegetation-change case only. We therefore conclude that accounting for changes in Saharan dust loadings is essential for improving model simulations of the WAM during the Mid-Holocene.

1. Introduction

Following the devastating droughts that ravaged the Sahel in the 1970–1980s, many efforts have been directed at investigating climate variability in Northern Africa, focusing on vegetation–climate feedbacks and the dynamics of the West African Monsoon (WAM) system (Charney et al., 1975; Giannini et al., 2003). However, the past millennia have witnessed much larger precipitation changes than those seen in recent decades. One of the most dramatic changes in the WAM began around 15000 yr BP, when increased summer precipitation led to an expansion of the North African lakes and wetlands. Grassland and shrubland covered areas that are currently desert (Holmes, 2008), giving origin to the so-called "Green Sahara", or African Humid Period. The African Humid Period ended between ~5500 and ~4000 yr BP (Armitage et al., 2015; deMenocal et al., 2000; Shanahan et al., 2015; Weldeab et al., 2007). Climate model simulations for the Mid-Holocene (MH, 6000 yr BP) are not currently able to fully reproduce the intensification and geographical expansion of the African monsoon (Harrison et al., 2014). Hargreaves et al. (2013) have shown that this is not a function of the resolution at which the data-model comparisons are made, and that the source of these discrepancies must lie in a shortcoming common to all models.

The Paleoclimate Modelling Intercomparison Project/Coupled Model Intercomparison Project (PMIP/CMIP) protocols assume the MH to have the same dust concentrations and land cover as the pre-industrial period (Taylor et al., 2009). However, paleo-proxy data indicate that dust emissions during the MH were 70–80% lower than today (Arbuszewski et al., 2013; deMenocal et al., 2000; McGee et al., 2013), and the Sahara desert was replaced to a great extent by shrubs and grassland (Holmes, 2008). The key to the models' dry bias may therefore be an incorrect representation of vegetation and dust concentrations. On the one hand, several studies have already shown that variations in vegetation and soil type can have a major impact on precipitation, similar in magnitude to that induced by orbital forcing (e.g., Braconnot et al., 1999, 2000; Chikira et al., 2006; Claussen and Gayler, 1997; Claussen et al., 1998; Krinner et al., 2012; Kutzbach and Liu, 1997; Kutzbach et al., 1996). Nevertheless, the precipitation increase due to land cover changes alone is not sufficient to correct the models' dry bias, revealing only partial agreement with the most recent paleo-data records (Harrison et al., 2014; Krinner et al., 2012; Lézine et al., 2011; Shanahan et al., 2015). On the other hand, there

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Table 1
Albedo and leaf area index (LAI) for desert, evergreen shrub and grassland/steppe and the domain over which the vegetation changes are applied in each set-up.

Vegetation type		Albedo	LAI	Domain
PS	Mainly desert	0.30	0.18	11°–33°N 15°W–35°E
		0.29	0.28	23°–33°N 15°E–35°E
GS	Evergreen shrub	0.15	2.6	11°–33°N 15°W–35°E
GS2	Evergreen shrub	0.15	2.6	11°–22°N 15°W–35°E 23°–33°N 15°W–14°E
	Grassland/steppe	0.25	1.0	23°–33°N 15°E–35°E

are yet no estimates of the potential impacts of Saharan dust reduction on the MH WAM. Changes in mineral dust loading can alter both incoming solar radiation and cloud properties (DeMott et al., 2003); they can further lead to changes in atmospheric and oceanic circulation (e.g., Evan et al., 2006; Serra et al., 2014; Wang et al., 2012), precipitation, storm development and sea surface temperatures (SSTs) (Booth et al., 2012; Evan et al., 2011, 2009). This points to dust as the potential gap in our current understanding of past WAM changes.

Here we use climate model simulations to examine the relative importance of vegetation and Saharan dust concentrations in affecting the MH WAM strength and in driving the associated atmospheric circulation changes. Our primary goal is to understand and quantify the role of dust reduction under a vegetated Sahara.

2. Model description and experimental set-up

2.1. The model

The present study uses the latest version of the fully coupled global climate model EC-Earth (version 3.1, Hazeleger et al., 2010). The atmospheric model is based on the Integrated Forecast System (IFS cycle 36r4) developed by the European Centre for Medium-range Weather Forecasts, including the H-TESSEL land model. The simulation is run at T159 horizontal spectral resolution (roughly 1.125°) with 62 vertical levels. The atmospheric component is coupled to the Nucleus for European Modelling of the Ocean version 2 (NEMO, Madec, 2008), developed at the Institute Pierre Simon Laplace, and the Louvain-la-Neuve Sea Ice Model version 3 (LIM3, Vancoppenolle et al., 2008). The coupling is performed by the OASIS 3 coupler (Valcke, 2006). The ocean component NEMO has a nominal horizontal resolution of 1° and 46 vertical levels. The EC-Earth version used in this study has prescribed vegetation. The aerosol concentrations are provided as prescribed fields. The aerosol indirect effects are not included in the model version used in this study. The annual cycle of the various aerosol types follows Tegen et al. (1997). A detailed description of the aerosol components can be found in Hess et al. (1998). In Table S1 we report the characteristics of the dust particles in our model.

2.2. Experiments set-up

We use as reference scenario the climate of the MH, with insolation and greenhouse gas concentrations from 6000 yr BP. Differences in the Earth's orbit in the MH enhanced the amplitude of the seasonal cycle in Northern Hemisphere insolation by ∼5% compared to present day values. In the control MH simulation (MH_{CNTRL}), we impose PI dust concentrations and vegetation over the Sahara (desert), as described in the CMIP5 protocol (Taylor et al., 2009). While it is well established that dust mobilization during the mid-Holocene was lower compared to the late Holocene, we follow the protocol to ease the comparison of our results to the literature. We also simulate the PI climate to validate the model and assess the impact of the orbital forcing alone (see Supplementary material). We then perform an idealized experiment ($MH_{GS\text{-}RD}$) in which the vegetation type over the Sahara (11°–33°N and 15°W–35°E) is set to shrub, typical of the modern Sudanian Savanna ecoregion, and the PI dust amount is reduced by up to 80% (Fig. S1), based on recent estimates of Saharan dust flux reduction during the MH (Arbuszewski et al., 2013; deMenocal et al., 2000; McGee et al., 2013). A recent model simulation using an atmospheric-aerosol model with an embedded scheme to detect potential dust sources has confirmed this massive dust emission reduction during the Mid-Holocene (Egerer et al., 2015). The vegetation change corresponds to a reduction in the surface albedo from ∼0.3 to 0.15 over the Sahara region and an increase in the leaf area index from ∼0.2 to 2.6 (desert and shrub respectively; Table 1). The dust reduction leads to a decrease in the global dust aerosol optical depth (AOD) of almost 60% and in the total AOD of 0.02 (Fig. 1 and Table S1). Finally, we perform two further experiments in which the pre-industrial Saharan dust concentrations and vegetation are changed in turn ($MH_{*S\text{-}*D}$).

The idealized set-up of the experiments enables a better investigation of the role of dust under a vegetated Sahara. Furthermore, recent proxy studies have shown that, during the African Humid Period, paleo-lakes extended at least up to 28°N (Lézine et al., 2011) and Sudanian Savanna type vegetation (dominated by shrubs) was centered between 20° and 25°N and reached as far as 28°N – about 6–9° latitude further north than the modern distribution (Hély et al., 2014). An earlier and commonly adopted vegetation reconstruction (Hoelzmann et al., 1998) does not account for such an extensive greening, instead prescribing steppe vegetation north of 20°N. In view of the above, the idealized vegetation cover in our sensitivity experiments may not be entirely unrealistic, especially in the Western Sahara. We have nonetheless tested the sensitivity of our results to the choice of the vegetation cover by performing an additional set of experiments in which the shrubland is replaced by grassland (steppe) over the eastern Sahara domain ($MH_{GS2\text{-}*D}$).

It is difficult to verify whether the imposed vegetation cover and dust reduction are consistent with one another without a fully interactive aerosol scheme. Nevertheless, the dust-scaling factor is based on proxy evidence and the imposed vegetation cover is consistent – in particular in the $MH_{GS2\text{-}*D}$ experiments – with the inferred large increase in precipitation, as discussed in Sections 3.4 and 4.

The details of the boundary conditions for the sensitivity experiments are listed in Table 2. Initial conditions were taken from a 700-year pre-industrial spin-up run, and the simulations were then run for approximately 300 yr. The climate reaches quasi-equilibrium after 100 to 200 yr, depending on the experiment. In this paper we focus on the equilibrium responses, and only the last 100 yr of each sensitivity experiment are analyzed.

2.3. Monsoon diagnostics

In order to quantify the impacts of Saharan dust and vegetation on the WAM, we define the onset, duration and northernmost