Quaternary Science Reviews 171 (2017) 119–135

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Millennial-scale fluctuations in Saharan dust supply across the decline of the African Humid Period

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ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form
10 July 2017
Accepted 11 July 2017
Available online 17 July 2017

Keywords:
Holocene
Palaeolimnology
Palaeoclimatology
North Atlantic
Western Mediterranean
Morocco
Sahara
Dust record
Inorganic geochemistry

ABSTRACT

The Sahara is the world's largest dust source with significant impacts on *trans*-Atlantic terrestrial and large-scale marine ecosystems. Contested views about a gradual or abrupt onset of Saharan aridity at the end of the African Humid Period dominate the current scientific debate about the Holocene Saharan desiccation. In this study, we present a 19.63 m sediment core sequence from Lake Sidi Ali (Middle Atlas, Morocco) at the North African desert margin. We reconstruct the interaction between Saharan dust supply and Western Mediterranean hydro-climatic variability during the last 12,000 yr based on analyses of lithogenic grain-sizes, XRF geochemistry and stable isotopes of ostracod shells. A robust chronological model based on AMS ^{14}C dated pollen concentrates supports our multi-proxy study. At orbital-scale there is an overall increase in southern dust supply from the Early Holocene to the Late Holocene, but our Northern Saharan dust record indicates that a gradual Saharan desiccation was interrupted by multiple abrupt dust increases before the 'southern dust mode' was finally established at 4.7 cal ka BP. The Sidi Ali record features millennial peaks in Saharan dust increase at about 11.1, 10.2, 9.4, 8.2, 7.3, 6.6, 6.0, and 5.0 cal ka BP. Early Holocene Saharan dust peaks coincide with Western Mediterranean winter rain minima and North Atlantic cooling events. In contrast, Late Holocene dust peaks correspond mostly with prevailing positive phases of the North Atlantic Oscillation. By comparing with other North African records, we suggest that increases in Northern Saharan dust supply do not solely indicate sub-regional to regional aridity in Mediterranean Northwest Africa but might reflect aridity at a *trans*-Saharan scale. In particular, our findings support major bimillennial phases of *trans*-Saharan aridity at 10.2, 8.2, 6.0 and 4.2 cal ka BP. These phases coincide with North Atlantic cooling and a weak African monsoon.

1. Introduction

The Sahara is the world's largest dust source (Ginoux et al., 2012; Goudie and Middleton, 2001) with significant impacts on *trans*-Atlantic terrestrial environments (Bristow et al., 2010; Muhs et al., 1990; Prospero and Lamb, 2003), Canary soil properties (Suchodoletz et al., 2013), Mediterranean forests (Avila et al., 1998) and large-scale marine ecosystems (Jickells et al., 2005; Mahowald et al., 2010). Remote Saharan dust influences the earth's radiation budget (Kaufman et al., 2002) and tropical North Atlantic ocean-atmosphere temperature variability (Evan et al., 2011) that might even attenuate Hurricane activity (Evan et al., 2016).

The intensity of Saharan dust mobilisation varies over different time-scales (Albani et al., 2015; Bout-Roumazeilles et al., 2013; Ehrmann et al., 2017; Goudie, 2009; Jullien et al., 2007; Kuhlmann et al., 2004). In the range of instrumental records and historical reanalyses, Sahelian droughts (Evan et al., 2016; Goudie and Middleton, 2001) and positive phases of the North Atlantic

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http://dx.doi.org/10.1016/j.quascirev.2017.07.010

Oscillation (Chiapello and Moulin, 2002; Ginoux et al., 2004; Mahowald et al., 2003; Moulin et al., 1997) are considered the two most important climatic drivers for accelerating Saharan dust mobilisation and its long-range dispersal. However, regarding the entire Holocene, a much longer time period that covers the last 11,700 years, the forcing mechanisms and frequencies of Saharan dust mobilisation remain controversial (deMenocal et al., 2000a; Kröpelin et al., 2008; Longman et al., 2017).

The orbital-scale increase in northern hemispherical summer insolation led to the large-scale expansion of the tropical rain belt and to the onset of the African Humid Period at about 14.8 cal ka BP (Shanahan et al., 2015). One of the most prominent ecological changes during the Holocene was the end of the African Humid Period with the transition from the 'green' Sahara towards the hyperarid desert today. With respect to different North African investigation sites, this mid-Holocene desiccation of the Sahara took place between 7 and 3 cal ka BP (Shanahan et al., 2015). Generally, an earlier onset of aridity can be observed at the northern Saharan margin at about 7 cal ka BP in contrast to relatively humid conditions that persisted at the southern Saharan margin until 3 cal ka BP (Shanahan et al., 2015). Alongside declining summer insolation, powerful vegetation-climate feedbacks may be implicated in the end of the African Humid Period (Renssen et al., 2006).

The mid-Holocene desiccation of the Sahara stopped the natural potential of North African geological archives for recording the Holocene environmental history of the world's largest desert. To date, there is only one terrestrial record from the Sahara itself that covers the last 6000 years. The Lake Yoa record (Fig. 1) documents a continuous and gradual desiccation from the Mid-Holocene until today (Kröpelin et al., 2008). In contrast, marine core ODP 658C (deMenocal et al., 2000a, Fig. 1) taken off the coast of NW-Africa documents an abrupt mid-Holocene onset of increased Saharan dust supply at ~5.0 cal ka BP. This abrupt shift is also visible with some uncertainty in marine cores of the tropical Western and subtropical North Atlantic (Williams et al., 2016). Modelling approaches indicate abrupt vegetation collapses as a response to gradual decreases in summer insolation and precipitation in the Western Sahara at that time (deMenocal et al., 2000a; Liu et al., 2007). However, due to the missing multi-proxy evidence from terrestrial archives in the Western Sahara itself, there are gaps in the knowledge about timing and extent of probable cross-Saharan desiccation during the Holocene. This leads to the controversial views about a gradual (Kröpelin et al., 2008; Kuper and Kröpelin, 2006; Shanahan et al., 2015) or abrupt (deMenocal et al., 2000a; Tierney et al., 2017) onset of Saharan desiccation at the end of the African Humid Period that dominate the current scientific debate (Egerer et al., 2016).

A 19.63 m long core from Lake Sidi Ali (Moroccan Middle Atlas) within the intercalation zone of North Atlantic and Saharan air mass trajectories (Figs. 1 and 2) provided for the first time a robustly dated (Fletcher et al., 2017) multi-proxy reconstruction of hydro-climatic variability at the North African desert margin for the last 12,000 years (Zielhofer et al., 2017). In the new study presented here, we aim to reconstruct from the same core the Holocene variability of Saharan dust supply. Selected siliciclastic element ratios from terrestrial sampling sites alongside a transect at the North African desert margin are used for the first time as geochemical tracers and compared with those ratios from the Sidi Ali core to gain information about shifting dust provenance. We compare shifts in dust provenance with changes in aeolian grain size. Finally, we evaluate probable synchronicities between Saharan dust mobilisation and the North Atlantic hydro-climate during the Holocene.

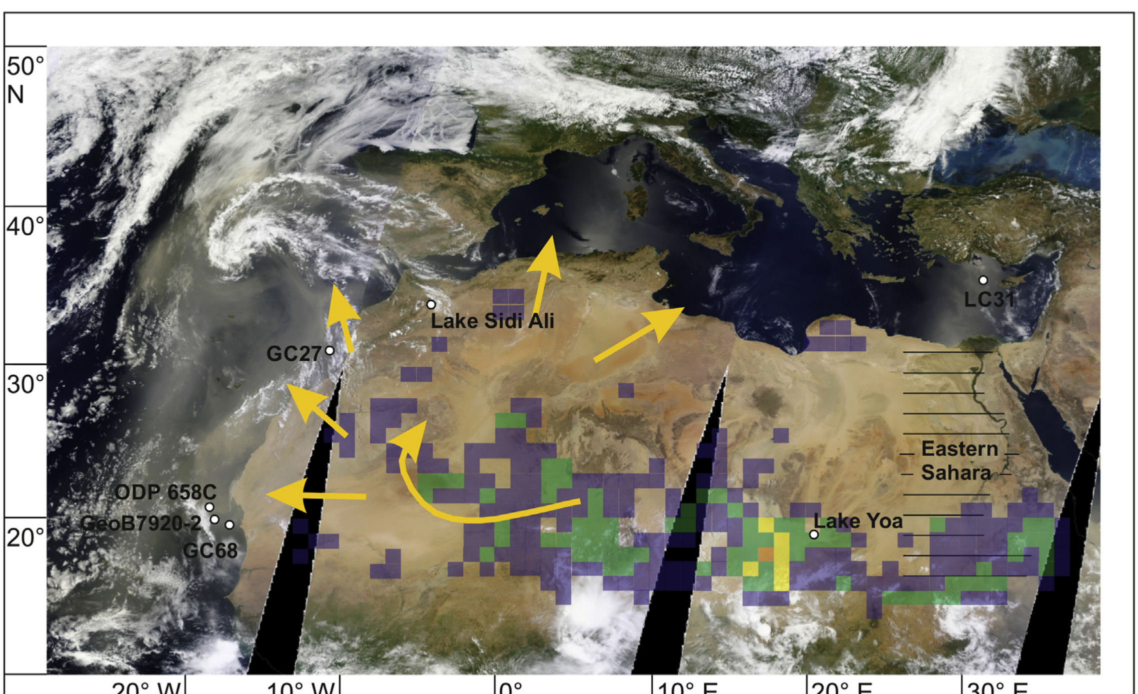

Fig. 1. Overview satellite image with major circum-Saharan sites discussed in this manuscript, showing Lake Sidi Ali (this study), Eastern Saharan geoarcheological record (horizontal lines, Kuper and Kröpelin, 2006), Central Saharan Lake Yoa (Ounianga Kebir, Kröpelin et al., 2008), off Morocco GC27 Site (Tierney et al., 2017), off Mauretania ODP Site 658C (deMenocal et al., 2000a, 2000b), off Mauretania GeoB7920-2 core (Tjallingii et al., 2008), off Mauretania GC68 Site (Tierney et al., 2017), and Eastern Mediterranean LC31 marine core (Schmiedl et al., 2010). Blue, green, yellow and orange backgrounds indicate moderate to major dust production areas based on MSG SEVIRI infrared dust index (Schepanski et al., 2009). Yellow arrows indicate major Saharan dust trajectories towards the subtropical North Atlantic and the Mediterranean Basin (Ashpole and Washington, 2013; Schepanski et al., 2016). The composed satellite images were obtained on 26 June 2012 by MODIS (Moderate Resolution Imaging Spectroradiometer) flying aboard NASA's Terra satellite (NASA, 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)