Quaternary Science Reviews 157 (2017) 29–51

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Atlantic forcing of Western Mediterranean winter rain minima during the last 12,000 years

Christoph Zielhofer [a,*], William J. Fletcher [b], Steffen Mischke [c], Marc De Batist [d], Jennifer F.E. Campbell [b], Sebastien Joannin [e], Rik Tjallingii [f], Najib El Hamouti [g], Annett Junginger [h], Andreas Stele [i], Jens Bussmann [i], Birgit Schneider [a], Tobias Lauer [a,j], Katrin Spitzer [k], Michael Strupler [l], Thomas Brachert [m], Abdeslam Mikdad [n]

[a] Institute of Geography, Leipzig University, Leipzig, Germany
[b] School of Environment and Development, University of Manchester, Manchester, United Kingdom
[c] Faculty of Earth Sciences, University of Iceland, Reykjavik, Iceland
[d] Renard Centre of Marine Geology, Ghent University, Ghent, Belgium
[e] Institut des Sciences de l'Evolution, Montpellier University, France
[f] GFZ German Research Centre for Geosciences, Section 5.2 – Climate Dynamics and Landscape Evolution, Potsdam, Germany
[g] Faculté Pluridisciplinaire Nador, Université Mohamed I Oujda, Morocco
[h] Faculty of Geosciences, Tübingen University, Germany
[i] Institute of Geography, Osnabruck University, Osnabruck, Germany
[j] Max Planck Institute for Evolutionary Anthropology, Department of Human Evolution, Leipzig, Germany
[k] Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany
[l] Department of Earth Sciences, ETH Zurich, Switzerland
[m] Institute of Geophysics and Geology, Leipzig University, Leipzig, Germany
[n] Institut National des Sciences de l'Archéologie et du Patrimoine, Rabat, Morocco

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form
22 September 2016
Accepted 29 November 2016

Keywords:
Holocene
Younger Dryas
Winter rain minima
Atlantic forcing
Western Mediterranean
North Atlantic Oscillation (NAO)
Seasonality
Solar forcing
Lake sediments
Middle Atlas
Morocco

ABSTRACT

The limited availability of high-resolution continuous archives, insufficient chronological control, and complex hydro-climatic forcing mechanisms lead to many uncertainties in palaeo-hydrological reconstructions for the Western Mediterranean. In this study we present a newly recovered 19.63 m long core from Lake Sidi Ali in the North African Middle Atlas, a transition zone of Atlantic, Western Mediterranean and Saharan air mass trajectories. With a multi-proxy approach based on magnetic susceptibility, carbonate and total organic C content, core-scanning and quantitative XRF, stable isotopes of ostracod shells, charcoal counts, *Cedrus* pollen abundance, and a first set of diatom data, we reconstruct Western Mediterranean hydro-climatic variability, seasonality and forcing mechanisms during the last 12,000 yr. A robust chronological model based on AMS ^{14}C dated pollen concentrates supports our high-resolution multi-proxy study. Long-term trends reveal low lake levels at the end of the Younger Dryas, during the mid-Holocene interval 6.6 to 5.4 cal ka BP, and during the last 3000 years. In contrast, lake levels are mostly high during the Early and Mid-Holocene. The record also shows sub-millennial- to centennial-scale decreases in Western Mediterranean winter rain at 11.4, 10.3, 9.2, 8.2, 7.2, 6.6, 6.0, 5.4, 5.0, 4.4, 3.5, 2.9, 2.2, 1.9, 1.7, 1.5, 1.0, 0.7, and 0.2 cal ka BP. Early Holocene winter rain minima are in phase with cooling events and millennial-scale meltwater discharges in the sub-polar North Atlantic. Our proxy parameters do not show so far a clear impact of Saharan air masses on Mediterranean hydro-climate in North Africa. However, a significant hydro-climatic shift at the end of the African Humid Period (~5 ka) indicates a change in climate forcing mechanisms. The Late Holocene climate variability in the Middle Atlas features a multi-centennial-scale NAO-type pattern, with Atlantic cooling and Western Mediterranean winter rain maxima generally associated with solar minima.

* Corresponding author.
E-mail address: zielhofer@uni-leipzig.de (C. Zielhofer).

http://dx.doi.org/10.1016/j.quascirev.2016.11.037

1. Introduction

Western Mediterranean environments are considered some of the most sensitive landscapes to global warming (Giorgi, 2006). Future climate changes in the Western Mediterranean region will enhance the occurrence of heat stress (Diffenbaugh et al., 2007) and droughts (Born et al., 2008) and will reduce mean annual precipitation (Solomon et al., 2009). In order to refine scenarios for future climate changes it is important to integrate palaeoclimatic data in climatic models (Flato et al., 2013). On this note, high-resolution continuous palaeoclimatic data from recovered lake sediments allow the reconstruction of past climatic oscillations and cycles on decadal- to millennial timescales (Corella et al., 2014). Furthermore, the compilation of continuous palaeoenvironmental proxy-data is a tool for reconstructing shifts and thresholds of natural landscape systems in response to gradual and rapid climatic forcing (Roberts et al., 2011; Fletcher and Zielhofer, 2013).

While Holocene global Rapid Climate Changes (RCCs) are generally characterised by cooling (Mayewski et al., 2004), regional to sub-regional changes in precipitation pattern appear to be much more important in the Western Mediterranean for environmental change. Evidence from numerous records points to perturbation of the Western Mediterranean hydrological regime during the Holocene. Geomorphological, palaeohydrological and palaeoecological records indicate hydro-climatic impacts on vegetation (Fletcher et al., 2013; Nourelbait et al., 2014), lake levels (Lamb et al., 1995; Pérez-Sanz et al., 2013), fire regimes (Linstädter and Zielhofer, 2010; Reddad et al., 2013), fluvial dynamics (Zielhofer et al., 2010; Wolf and Faust, 2015) and aeolian sediment mobilisation (Bout-Roumazeilles et al., 2013). While it is already challenging to link phases of aridity and humidity on a sub-regional to regional scale (Carrión, 2002; Benito et al., 2015), the reconstruction of past Mediterranean hydro-climate becomes more complex by integrating varying seasonality (Lamb et al., 1995).

Current studies and reviews of Holocene palaeoclimatic changes at continental scales of the Atlantic realm mainly focus on temperate (Magny et al., 2012; Moreno et al., 2014a) or monsoonal (Shanahan et al., 2015) air mass variability. However, there is only scarce knowledge of hydro-climatic interaction at the Northern Saharan desert margin, a zone of transition with current impacts of Atlantic, Western Mediterranean and Saharan air masses. Well-dated and high-resolution studies of the palaeoenvironmental evolution of the Middle Atlas mountainous desert margin are required to understand climatic interactions in this zone.

Despite pioneering palaeolimnological works in the Middle Atlas (El Hamouti, 1991, Barker et al., 1994; Lamb et al., 1995, 1999; Lamb and van der Kaars, 1995; Cheddadi et al., 1998) and recent palaeoenvironmental studies (e.g. Nourelbait et al., 2014, 2015) including a focus on anthropogenic impacts (Cheddadi et al., 2015), there remains a need for continuous records with robust chronologies in Mediterranean North Africa, which allow a clear coupling with continuous climatic archives in the wider region. For example, while Lamb et al. (1995) detect sub-millennial-scale impacts of Atlantic air masses on the Holocene hydro-climate in Mediterranean North Africa, the forcing mechanisms (Fletcher et al., 2013), timing, and impacts on Western Mediterranean environments (McGregor et al., 2009) are still under debate.

The aim of this study is the reconstruction of the centennial-scale hydro-climatic history of the Middle Atlas as a mountainous Saharan desert margin based on a stratigraphical multi-proxy approach and a hydrological sampling program at Lake Sidi Ali. We aim to develop a pollen-based ^{14}C chronology to reduce hard-water induced errors in radiocarbon dating of lacustrine sediments and to create the most robust terrestrial chronology for Morocco and of relevance to the Western Mediterranean in a broader scale. The approach should yield insights into orbital-, sub-millennial and centennial-scale climatic variability of the Western Mediterranean at its zone of transition towards the Sahara in the South, including evaluation of the role of climatic forcing by North Atlantic cooling episodes, ice-rafting (Bond events) and solar variability. The study aims to trace shifting impacts of Atlantic, Mediterranean and southern air mass trajectories and to gain knowledge about their variability, seasonality and forcing mechanisms. This knowledge is ultimately valuable for extending the understanding of key modes of climatic variability, such as the North Atlantic Oscillation (NAO), beyond the limits of historical and tree-ring records (Trouet et al., 2009).

2. Geographical setting

Lake Sidi Ali (33° 03′N, 5° 00′W, 2080 m a.s.l.) is located in the Middle Atlas, Morocco (Fig. 1a). The lake lies in a depression of structural origin along a fault-line between Middle Jurassic limestone in the south-east and Lower Jurassic dolomite in the north-west (Fig. 1b). The northern boundary of Lake Sidi Ali is prescribed by the Plio-Pleistocene Sidi Ali volcano. The catchment includes mountains reaching 2220–2338 m. The surrounding forest vegetation of evergreen oak (*Quercus rotundifolia*) and Atlantic cedar (*Cedrus atlantica*) is representative of the montane Mediterranean bioclimatic zone but degraded due to overgrazing.

The lake lies within a small, closed catchment of approx. 14 km^2 and has a varying surface between 2.0 and 2.8 km^2 due to high sensitivity with respect to changes in precipitation/evaporation balance (Sayad et al., 2011). Depending on water level fluctuations, the lake may be separated in two sub-basins by a basalt ridge, as it has been since 1974 (Barker et al., 1994). Previous research on the southern shallow sub-lake (Barker et al., 1994; Lamb et al., 1999) indicates a minimum sediment depth of 635 cm covering a time-span from 0 to 7 cal ka BP. The main lake (Fig. 1b) was never drilled before from a raft.

The mean annual precipitation (1982–2009) is 430 mm at Lake Sidi Ali. The dry season lasts from June to September and the wet period from October to May (Fig. 1c). The position of the lake is within a strong N-S hydrological gradient and reflects a mountainous desert margin between the sub-humid Mediterranean climate in the north and the arid to semiarid High Atlas in the south (Linstädter and Zielhofer, 2010). The mean annual temperature is 10.3 °C with a minimum in January of 2.0 °C and a maximum in July of 19.7 °C.

3. Methods

3.1. Bathymetric and acoustic sub-bottom profiling

Lake Sidi Ali was surveyed in September 2012 with a high-resolution acoustic system (pinger with 3.5 kHz central frequency) mounted on a cataraft attached on the side of a motorized raft (cruising speed 3.5 knots). The data were acquired and processed with DELPH Seismic Acquisition Software (IXBLUE) and interpreted with IHS Kingdom 8.7 Software. For the calculation of water depths, a p-wave velocity of 1500 m/s was used. Bathymetric and seismic data were used to create a bathymetric map, to investigate the stratigraphy of the lake infills and to inform the positioning of coring site.

3.2. Hydrological analyses

A hydrological survey was also undertaken in September 2012, sampling streams and springs in the vicinity of the lake (Fig. 1b). At each sampling locality, pH value, specific conductivity and oxygen