



Research article

Leaf wax δD inferring variable medieval hydroclimate and early initiation of Little Ice Age (LIA) dryness in southern Mozambique

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ABSTRACT

A sediment sequence from a coastal, hydrologically isolated lake in southern Mozambique was analysed for leaf wax δD , *n*-alkane abundance (ACL) and bulk organic geochemistry ($\delta^{13}C$, TOC, %N), providing a record of past rainfall variability and savanna dynamics over the last 1500 years. The δD_{wax} rainfall reconstruction reveals a stable hydroclimate between 500–700 CE, while ACL and $\delta^{13}C$ together with previous pollen data suggest savanna vegetation was characterized by a relatively dense woody cover. Highly variable hydroclimate conditions are inferred by δD_{wax} between 800–1350 CE, with repeated centennial scale intervals of extreme dry and wet conditions overlapping the Medieval Climate Anomaly (MCA; 950–1250 CE). Savanna tree cover stayed relatively intact over this phase. After ca 1250 CE, a progressive change towards drier conditions was initiated, leading up to maximum aridity during the AD 1700s, a period associated with the Little Ice age (LIA; 1500–1850 CE). Tree cover was now replaced by a more grass-dominated savanna. The clear antiphase rainfall patterns between Nhaucati and equatorial East African proxy records gives support to the notion that Indian Ocean sea surface temperature (SST) gradients act as modulator of southern African climate on a multi-decadal time scale, possibly forced by long-term El Niño Southern Oscillation (ENSO) variability. We suggest that strong ENSO variability and greater occurrence of La Niña events triggered the generally wet and unstable MCA in southern Africa. From around 1250 CE, a shift towards a predominance of El Niño induced drier conditions in south-east Africa during the LIA. Our study of vegetation and hydroclimate proxies in parallel suggests that savanna tree and shrub cover was relatively resilient to the abrupt shifts in hydroclimate over the MCA, but more sensitive to the long-term progressive drying over the LIA.

1. Introduction

The amount and general quality of proxy-based climate reconstructions from Africa are currently too limited to support a regional climate change assessment (Masson-Delmotte et al., 2013). As a consequence, the last IPCC report encourages generation of additional unambiguous and high-resolution proxy-records, especially from southern Africa where available paleo-data are particularly sparse (Nash et al., 2016). The south-eastern part of the African subcontinent is a key region for identifying past shifts in the climate system due to its location at the boundary between the tropics and subtropics and thereby sensitivity to hydroclimate change associated with latitudinal fluctuations in atmospheric circulation systems (Schneider et al., 2014).

Southern African regional rainfall dynamics are also strongly linked to eastern equatorial hydroclimate in an anti-phase fashion. On decadal to centennial time scales, rainfall variability along the east African coast is modulated by large-scale processes such as sea surface temperature (SST) gradients over the Indian Ocean (Saji et al., 1999; Tierney et al., 2013) and land-ocean temperature contrasts along the African east coast (Zhang et al., 2015). Moreover, southeastern Africa is sensitive to teleconnective forcing from the El Niño Southern Oscillation (ENSO), causing extreme droughts during strong El Niño phases and wetter conditions during La Niña phases (Camberlin et al., 2001; Nicholson, 1986). As ENSO activity is likely to change character due to present global warming, effects on hydroclimate in southeastern Africa can be expected. Statistical comparison of ENSO activity and South African

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summer temperatures between 1940–2016 CE reveals a warming effect from El Niño events which is particularly strong during the last ca 40 years (Lakhraj-Govender and Grab, 2018). However, climate models disagree in whether global warming will amplify or mute the ENSO variability (Guilyardi et al., 2009; Collins et al., 2010; An and Choi, 2015). In this context, the study of paleo-climate over the late Holocene (last 2000 years) is of central importance due to its close analogue with present day boundary conditions, allowing assessment of potential future impacts on hydroclimate and ENSO variability from expected global warming. Moreover, the impact of past climatic shifts on ecosystem response may inform on how modern vegetation analogues will respond to future climate change.

Here we present a water-isotope based hydroclimate record covering the last 1500 years from Lake Nhaucati, a hydrologically isolated coastal lake in southern Mozambique. The lake was previously investigated for pollen and diatoms (Ekblom, 2008; Ekblom and Stabell, 2008), providing a coarse-scale paleo-record which is utilized to frame the new data in a paleo-ecological context, and to deduce potential vegetation biases on the isotopic record.

Water isotopes (typically expressed on a delta scale as $\delta^{18}\text{O}$, $\delta^2\text{H}$ or δD) are excellent recorders of past hydrological conditions, as their composition is known to fluctuate in accordance with climate-related factors (Dansgaard, 1964). The use of the hydrogen isotope composition (δD) of sedimentary organic biomarkers has opened up for a wider geographical coverage of water isotope-based records worldwide (Sachse et al., 2012). Long-chain *n*-alkanes derived from terrestrial leaf waxes are particularly suitable for paleo-studies as they stay well preserved over geological time scales, yet leaving their isotopic signature essentially intact (Peters et al., 2005). Furthermore, *n*-alkane chain length distributions are related to plant functional types, as algae and aquatic plants generally form short (*n*-C_{17–21}) and mid- (*n*-C_{23–25}) chain lengths, while terrestrial plants produce longer carbon chains (*n*-C_{27–35}) (Ficken et al., 2000; Aichner et al., 2010; Bush and McInerney, 2013). Although the leaf wax *n*-alkane hydrogen isotope composition ($\delta\text{D}_{\text{wax}}$) is affected by a fractionation during biosynthesis (e.g. Feakins and Sessions, 2010), its temporal variability has proven to reflect the isotopic changes in plant source water, e.g. of the lake water or precipitation ($\delta\text{D}_{\text{prec}}$) (e.g. Sachse et al., 2004; Aichner et al., 2010; Sachse et al., 2012; Tipple et al., 2013).

Based on the tropical and coastal setting, Lake Nhaucati leaf-wax δD can primarily be interpreted as a proxy for rainfall amount (Rozanski et al., 1993), although minor secondary fractionation effects from evapotranspiration may be expected. Furthermore, we use the *n*-alkane abundance and chain length data to confirm, highlight and lift new aspects of previous reports on regional savanna dynamics (Ekblom et al., 2014a; Norström et al., 2018a). We constrain the findings by considering pollen and diatom analysis performed on the same sediment sequence (Ekblom, 2008; Ekblom and Stabell, 2008). The new paleo-hydrological and vegetation records are compared with previous regional paleo-assessments, and tentative drivers of past hydro-climate variability and vegetation dynamics over the late Holocene period are discussed.

2. Regional setting and local site characteristics

Lake Nhaucati is located in southeastern Africa, ca. 5 km south of the town Vilanculos, along the coastal plain of southern Mozambique (22° 02'16.01"S, 35°18'43.48"E, Fig. 1). The lake is situated ca. 2 km from the coast, at an altitude of 20 m.a.s.l., covering an area of ca. 40 ha, with an east-west diameter of ca. 750 m. and a north-south diameter of ca. 500 m. The lake is one of many smaller lakes in the Vilanculos region. It has no surficial inlets or outlets, and lake levels are instead regulated by direct rainfall and recharge of ground water through shallow aquifers (Coetsee and Hartley, 2001), probably modulated by shifts in evaporation.

Climate is classified as semi-arid as annual potential

evapotranspiration (1440 mm) exceeds annual precipitation amounts (830 mm) (FAO, 1984). Air temperatures vary between ca. 27 °C during summer and ca. 19 °C during winter (FAO, 1984). Precipitation in the area is strictly seasonal with majority of rains falling between November and March, when the Intertropical Convergence Zone (ITCZ) is in its southernmost position and easterly trade winds bring moisture over the continent from the Indian Ocean (Tyson and Preston-Whyte, 2000). Although tropical cyclones are the major rainfall source in this coastal area, the tropical temperate troughs (TTTs) constitute another important rainfall contributor, manifested as NW-SE-stretching cloud bands, connecting the tropical and mid-latitude climate systems, producing convective and frontal summer rains in southern Africa (Harrison, 1984; Hart et al., 2010).

The coastal stretch of southern Mozambique consist of ancient sand dunes of Pleistocene and Holocene age, forming an undulating landscape with ridges stretching in a SE-NW direction (Spaliviero et al., 2014). Pleistocene dunes predominate in the area surrounding the lake, covering the Tertiary Jofane Formation limestone (Salman and Abdula, 1995). The thickness of the dune deposit is spatially variable, but generally thicker shoreward and less thick towards inland areas. The dunes consist of semi-consolidated red sand in the lower part and unconsolidated gray sand in the upper part, and are classified as internal dunes (DNG, 2006), with parabolic shapes formed under the dominating easterly wind pattern.

Vegetation in southern coastal Mozambique is characterized by coastal mosaics, forming a mixed floral composition, including Miombo savanna and woodlands with low density of small trees and shrubs combined with a grassy understorey (Wild and Fernandes, 1968). The open savanna vegetation in the Chibueni area and around Lake Nhaucati is dominated by herbs and grasses such as *Eragrostis ciliaris*, *Panicum maximum*, *Cyperus* spp., *Cenchrus incertus* and *Digitaria* spp., together with small Miombo tree components, mainly represented by *Julbernardia globiflora* and *Strychnos spinosa* (Ekblom and Stabell, 2008). Large areas of the land surrounding the lake are used for cultivation. The floral composition changes towards the sea, with a higher proportion of littoral shrubs such as *Commiphora zanzibarica*, *Phyllanthus reticulatus*, *Turra nilotica*, *Grewia monticola*, *Deinbollia oblongifolia*, *Clerodendrum glabrum* and *Acalypha glabrata*, as well as the climber *Cocculus hirta* (Ekblom, 2004).

3. Methods

3.1. Coring, subsampling and sample preparation

A 230 cm long sediment sequence was sampled with a Russian corer in the deepest part of the lake. The lithology was homogeneous throughout the sequence, dominated by gyttja of dark brown colour, but with increasing input of minerogenic components in the lowermost section, below 215 cm. The core was subsampled every 1 cm and stored in a freezer prior to chemical treatment. Details on coring methodology and lake bathymetry are available in Ekblom and Stabell (2008) and Ekblom (2008).

Ca. 2–6 g of sediment from 93 levels of the Nhaucati core were freeze-dried and homogenized. A small amount from each sample (5–10 mg) was weighed for bulk isotope measurements. The rest of each sample was used for lipid extraction. Total lipid extracts obtained via sonication of the dried sediments were fractionated into fractions containing only saturated hydrocarbons – dominated by the long-chain *n*-alkanes – using silica-gel based solid phase extraction. This procedure is described in detail elsewhere (Norström et al., 2017).

3.2. Bulk organic geochemistry and carbon isotope measurements

Bulk plant $\delta^{13}\text{C}$ was measured using a Carlo Erba NC2500 analyser, connected via a split interface to a Finnigan MAT Delta V mass spectrometer, at the Stable Isotope Laboratory, Stockholm University.

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