Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 184 (2016) 55–70

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

The stable hydrogen isotopic composition of sedimentary plant waxes as quantitative proxy for rainfall in the West African Sahel

Eva M. Niedermeyer[a,b,*], Matthew Forrest[b], Britta Beckmann[c], Alex L. Sessions[a], Andreas Mulch[b,d], Enno Schefuß[c]

[a] *Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, USA*
[b] *Senckenberg – Biodiversity and Climate Research Centre (BiK-F), 60325 Frankfurt, Germany*
[c] *MARUM – Center for Marine Environmental Sciences, University of Bremen, 28359 Bremen, Germany*
[d] *Institute for Geosciences, Goethe University Frankfurt, 60438 Frankfurt/Main, Germany*

Received 31 July 2015; accepted in revised form 25 March 2016; available online 4 April 2016

Abstract

Various studies have demonstrated that the stable hydrogen isotopic composition (δD) of terrestrial leaf waxes tracks that of precipitation (δD_{precip}) both spatially across climate gradients and over a range of different timescales. Yet, reconstructed estimates of δD_{precip} and corresponding rainfall typically remain largely qualitative, due mainly to uncertainties in plant ecosystem net fractionation, relative humidity, and the stability of the amount effect through time. Here we present δD values of the C_{31} *n*-alkane (δD_{wax}) from a marine sediment core offshore the Northwest (NW) African Sahel covering the past 100 years and overlapping with the instrumental record of rainfall. We use this record to investigate whether accurate, quantitative estimates of past rainfall can be derived from our δD_{wax} time series. We infer the composition of vegetation (C_3/C_4) within the continental catchment area by analysis of the stable carbon isotopic composition of the same compounds ($\delta^{13}C_{wax}$), calculated a net ecosystem fractionation factor, and corrected the δD_{wax} time series accordingly to derive δD_{precip}. Using the present-day relationship between δD_{precip} and the amount of precipitation in the tropics, we derive quantitative estimates of past precipitation amounts. Our data show that (a) vegetation composition can be inferred from $\delta^{13}C_{wax}$, (b) the calculated net ecosystem fractionation represents a reasonable estimate, and (c) estimated total amounts of rainfall based on δD_{wax} correspond to instrumental records of rainfall. Our study has important implications for future studies aiming to reconstruct rainfall based on δD_{wax}; the combined data presented here demonstrate that it is feasible to infer absolute rainfall amounts from sedimentary δD_{wax} in tandem with $\delta^{13}C_{wax}$ in specific depositional settings.

Keywords: *n*-alkanes; δD_{wax}; Leaf waxes; $\delta^{13}C_{wax}$; NW Africa; Sahel; Rainfall; δD_{precip}

1. INTRODUCTION

The stable hydrogen isotopic compositions (δD) of sedimentary higher-plant leaf waxes (δD_{wax}) are linked to the δD value of precipitation (δD_{precip}; summarized by Sachse et al., 2012), and multiple studies have employed δD_{wax} to infer past changes in Northwest (NW) African rainfall (Schefuß et al., 2005; Niedermeyer et al., 2010; Collins

* Corresponding author at: Senckenberg – Biodiversity and Climate Research Centre (BiK-F), 60325 Frankfurt, Germany.
E-mail address: eva.niedermeyer@senckenberg.de (E.M. Niedermeyer).

http://dx.doi.org/10.1016/j.gca.2016.03.034
0016-7037/

et al., 2013; Kuechler et al., 2013). In the tropics, the δD value of precipitation (δD_{precip}) is linked primarily to rainfall intensity (i.e. via the "amount effect"; Dansgaard, 1964; Rozanski et al., 1993), with decreasing values of δD_{precip} associated with increasing rates of precipitation. This information is recorded in higher-plant leaf waxes, with a fractionation between δD_{precip} and δD_{wax} due to metabolic isotope effects. The magnitude of this apparent fractionation, however, differs between plants, a fact that complicates the accurate, quantitative reconstruction of absolute rainfall amounts based on δD_{wax}. The conventional explanation is that this difference in apparent stable hydrogen isotope fractionation is a function of plant-morphological types (see Sachse et al., 2012), although more recent work suggests a phylogenetic origin (Gao et al., 2014a). Differences in stomatal conductance during photosynthesis and associated variance of leaf water enrichment through leaf transpiration, together with specific carbon allocation strategies of different plants are thought to be of particular importance in this regard (Smith and Freeman, 2006; McInerney et al., 2011; Kahmen et al., 2013a,b; Gao et al., 2014a). Such effects may be of particular importance in arid to semi-arid climates (Feakins and Sessions, 2010a, b), together with evaporative soil water enrichment under low ambient relative humidity. In addition, changes of precipitation source through time and its isotopic composition (e.g. through changes in atmospheric circulation or glacial-interglacial changes in ice volume) exert additional control on δD_{precip} that is not linked to the amount effect. As all these variables are difficult to assess in the paleorecord, δD_{wax}-based estimates of past rainfall changes have thus far remained mostly qualitative, i.e. "more" vs. "less" rainfall.

Strictly speaking, the amount effect is a measure of the amount of rainfall during individual precipitation events with rainfall intensity controlling re-evaporation, and, as a consequence, isotopic enrichment of the falling rain (Dansgaard, 1964; Rozanski et al., 1993; Worden et al., 2007; Lee and Fung, 2008; Risi et al., 2008a,b). This effect generally leads to lower δD values (that is stronger D-depletion through reduced re-evaporation) in areas of high precipitation and higher values (D-enrichment through higher re-evaporation) when precipitation is low. This relationship has been found to average $-4‰\ mm^{-1}\ day^{-1}$ (Bony et al., 2008) based on nine tropical marine GNIP (Global Network of Isotopes in Precipitation) stations. Recent studies indicate that e.g. the rainout history of monsoonal moisture (or changes in large-scale atmospheric circulation in general) may exert additional control on local δD_{precip} (e.g. Dayem et al., 2010; Pausata et al., 2011). This seems to be of particular importance in the equatorial Indo-Pacific realm, whereas the isotopic composition of incoming vapor remains relatively constant in sub-tropical coastal regions (Lee and Fung, 2008).

Sedimentary δD_{wax} values integrate δD_{precip} of multiple rainfall events by the formation leaves and associated leaf-wax production (Richardson et al., 2005). Multiple studies show that leaf waxes are produced (and replaced) continuously during the growing season (Pedentchouk et al., 2008; Sachse et al., 2009; Gao et al., 2012, 2015; Gao and Huang, 2013), fuelling debate on whether δD values of leaf waxes in soils represent δD_{precip} of the last weeks before leaf senescence rather than an integrated record of the growing season. In contrast, other studies indicate little or no wax production after a leaf is fully developed (Sachse et al., 2010; Kahmen et al., 2011a; Tipple et al., 2013). However, as multiple leaves are being produced at different times during the growing season, and as leaf waxes are eroded throughout the rainy season (Baker and Hunt, 1986), sedimentary δD_{wax} is most likely indicative of the amount of rainfall received during the growing season.

Changes in the amount of rainfall can be associated with changes in both rainfall intensity as well as wet season length. For example, the present-day variability of western Sahel hydroclimate is dominated by the amount of rain that falls during the rainy season rather than by wet-season length or abnormal rainfall during the dry season (Nicholson et al., 2013). On the other hand, long-term changes in western Sahel rainfall such as those induced by millennial-scale ITCZ (intertropical convergence zone) migration and tropical rain belt position have resulted in both changes in rainfall intensity and wet season length (Niedermeyer et al., 2010).

The stable carbon isotopic composition of sedimentary leaf waxes ($\delta^{13}C_{wax}$) has proven to be a valuable measure of the underlying type of vegetation (C_3 or C_4 photosynthetic pathway; Huang et al., 2000; Schefuß et al., 2003; Vogts et al., 2012). Although this does not account for all possible changes in vegetation – in particular the large variability within C_3 plants (trees, shrubs, C_3 grasses etc.) cannot be resolved – it nevertheless reflects vegetation changes in semi-arid to arid settings such as NW Africa reasonably well. This is because here, the major plant types contributing leaf waxes to the sedimentary record are tropical grasses (C_4) together with shrubs and trees (both C_3). As the abundance of C_4 plants is sensitive to wet season length and wet season temperature (winter vs. summer rain), both wet season intensity and wet season length can potentially be reconstructed from $\delta^{13}C_{wax}$ (Ehleringer et al., 1997; Niedermeyer et al., 2010; Collins et al., 2013). It is however noteworthy that in the past (e.g. during the last glacial) changes in atmospheric CO_2 concentration may have affected the C_3/C_4 composition of Sahel vegetation (Ehleringer et al., 1997), introducing a potential bias on inferred changes in rainy season length.

Despite the multiple controls on leaf wax δD values, several studies have attempted to quantify δD_{precip} from sedimentary δD_{wax} records. Tierney et al. (2010b) corrected their δD_{wax} record from Pleistocene sediments from Lake Tanganyika (East Africa) for changes in global ice volume and applied a constant apparent D-fractionation factor for vegetation to derive values of δD_{precip}. They infer a minor impact of vegetation change at their site on δD_{wax} but suggest changes in relative humidity over time to be the most critical variable amplifying the amount effect. Feakins (2013) and Feakins et al. (2012) in turn accounted for changing vegetation by pairing δD_{wax} with pollen and $\delta^{13}C_{wax}$ analysis in Miocene records from the Gulf of Aden and Antarctica. Based on their estimate of vegetation composition through time, they calculated time-varying