Quaternary Science Reviews 65 (2013) 88–101

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

Estimating the hydrogen isotopic composition of past precipitation using leaf-waxes from western Africa

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ARTICLE INFO

Article history:
Received 29 October 2012
Received in revised form
11 January 2013
Accepted 13 January 2013
Available online

Keywords:
Leaf-waxes
Hydrogen isotopic composition of precipitation
Organic geochemistry
African palaeoclimate

ABSTRACT

The hydrogen isotopic composition of plant leaf-wax *n*-alkanes (δD_{wax}) is a novel proxy for estimating δD of past precipitation (δD_p). However, vegetation life-form and relative humidity exert secondary effects on δD_{wax}, preventing quantitative estimates of past δD_p. Here, we present an approach for removing the effect of vegetation-type and relative humidity from δD_{wax} and thus for directly estimating past δD_p. We test this approach on modern day (late Holocene; 0–3 ka) sediments from a transect of 9 marine cores spanning 21°N–23°S off the western coast of Africa. We estimate vegetation type (C_3 tree versus C_4 grass) using $\delta^{13}C$ of leaf-wax *n*-alkanes and correct δD_{wax} for vegetation-type with previously-derived apparent fractionation factors for each vegetation type. Late Holocene vegetation-corrected δD_{wax} (δD_{vc}) displays a good fit with modern-day δD_p, suggesting that the effects of vegetation type and relative humidity have both been removed and thus that δD_{vc} is a good estimate of δD_p. We find that the magnitude of the effect of C_3 tree – C_4 grass changes on δD_{wax} is small compared to δD_p changes. We go on to estimate δD_{vc} for the mid-Holocene (6–8 ka), the Last Glacial Maximum (LGM; 19–23 ka) and Heinrich Stadial 1 (HS1; 16–18.5 ka). In terms of past hydrological changes, our leaf-wax based estimates of δD_p mostly reflect changes in wet season intensity, which is complementary to estimates of wet season length based on leaf-wax $\delta^{13}C$.

1. Introduction

The stable hydrogen isotopic composition (*D*/*H* ratio; expressed relative to the VSMOW standard as δD) of precipitation is a useful indicator of hydrology and climate dynamics. In the tropics it reflects both local precipitation amount and non-local rainout processes and is thus an indicator for both local- and large-scale atmospheric circulation changes. Sedimentary leaf-wax *n*-alkanes derived from terrestrial plants represent an archive of the hydrogen isotopic composition of past precipitation (δD_p) and are thus a useful proxy of past atmospheric dynamics. However, the interpretation of leaf-wax δD (δD_{wax}) records is complex because δD_{wax} is also affected by vegetation life-form and relative humidity (Sachse et al., 2012). Leaf-wax δD records have therefore been interpreted as reflecting past relative humidity and/or precipitation δD_p changes (Schefuß et al., 2005; Tierney et al., 2008; Niedermeyer et al., 2010), while concerns that vegetation-type changes may dominate δD_{wax} have also been raised (Smith and Freeman, 2006; Douglas et al., 2012). A quantitative estimate of past δD_p is therefore desirable for accurate climate reconstructions. We use a new approach, using estimates of vegetation type to correct for the effect of vegetation type and relative humidity on δD_{wax}. We test this approach on modern-day (late Holocene; 0–3 ka) marine sediments from a transect of 9 well-dated, high-resolution cores. These span from 21°N to 23°S off the coast of western Africa, covering West Africa, Central Africa and southwestern Africa (Table 1, Fig. 1a). Marine sediment cores have relatively large catchment areas and thus integrate the leaf-wax signal from a large continental area. Moreover, the large scale coverage of our mapping approach provides a valuable dataset for comparison with δD_p estimates from climate models. As well as the modern day, we also analyse: the mid-Holocene (6–8 ka) to test the effect of increased northern hemisphere summer insolation; the Last Glacial Maximum (19–23 ka) to test the effect of glacial conditions and Heinrich Stadial 1 (16–18.5 ka) to test the effect of Atlantic meridional overturning circulation slowdown on African climate. These time periods can be compared with climate modelling experiments.

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http://dx.doi.org/10.1016/j.quascirev.2013.01.007

Table 1
Core transect off western Africa.

Figure label	Region	Core number	Latitude	Longitude	Water depth (m)
1	West	GeoB7920-2	20° 45.09′ N	18° 34.90′ W	2278
2	West	GeoB9508-5	15° 29.90′ N	17° 56.88′ W	2384
3	West	GeoB9526-5	12° 26.10′ N	18° 03.40′ W	3223
4	West	GeoB9535-4	8° 52.54′ N	14° 57.66′ W	669
5	Central	GeoB4905-4	2° 30.00′ N	9° 23.40′ E	1328
6	Central	GeoB6518-1	5° 35.30′ S	11° 13.30′ E	962
7	Central	ODP1078C	11° 55.27′ S	13° 24.02′ E	500
8	Southwestern	GeoB1023-5	17° 09.43′ S	11° 00.70′ E	1978
9	Southwestern	MD08-3167	23° 18.91′ S	12° 22.61′ E	1948

2. Background

2.1. Spatial pattern of precipitation in West, Central and southwestern Africa

Most of the rain falling in tropical Africa is delivered by large convective storms known as mesoscale convective systems (Mohr and Zipser, 1996; Mohr et al., 1999; Nesbitt et al., 2006). Uplift required to create this convective rainfall is associated with the convergence of trade winds at the Intertropical Convergence Zone (West and Central Africa) and Congo Air Boundary (Central and southwestern Africa) and also with ascending air between the African Easterly Jet and Tropical Easterly Jet streams (Nicholson and Grist, 2003). These features, which collectively form the rainbelt, oscillate latitudinally along with the seasonal insolation maximum (Nicholson and Grist, 2003). The rainbelt oscillates between extremes of ~17°N in Jun–Jul–Aug (Fig. 1a) and ~21°S in Dec–Jan–Feb (Fig. 1c). In West and Central Africa, moisture for convective rainfall originates mostly from the Atlantic Ocean (Fig. 1a, b, d) and in southwestern Africa from the Indian Ocean (Fig. 1c; Rouault et al., 2003; Gimeno et al., 2010). Moisture is also recycled from the continent (either evaporated from soils and lakes or transpired from leaves; Peters and Tetzlaff, 1988; Taupin et al., 2000; Gimeno et al., 2010). The Sahara and Namib Deserts receive very little monsoonal precipitation. However, coastal fog, associated with cold upwelled waters (e.g. Olivier and Stockton, 1989), is common in Namibia and is an important source of moisture for plants (Louw and Seeley, 1980; Lancaster et al., 1984; Eckardt et al., in press). The wet season (which we define as the period of the year when rainfall is greater than 5 cm per month) is longest in the Congo Basin and Guinea coast regions (these regions experience two wet seasons per year) and decreases towards the desert regions. The wet season is most intense in the coastal Guinea and Cameroon regions and this is associated with topography, proximity to moisture source and the perpendicular orientation of winds to the coast (Hayward and Oguntoyinbo, 1987; Sall et al., 2007).

2.2. Temporal and spatial pattern of modern-day precipitation δD

In the tropics, the hydrogen isotopic composition of precipitation is dominated by the amount effect (Dansgaard, 1964; Rozanski

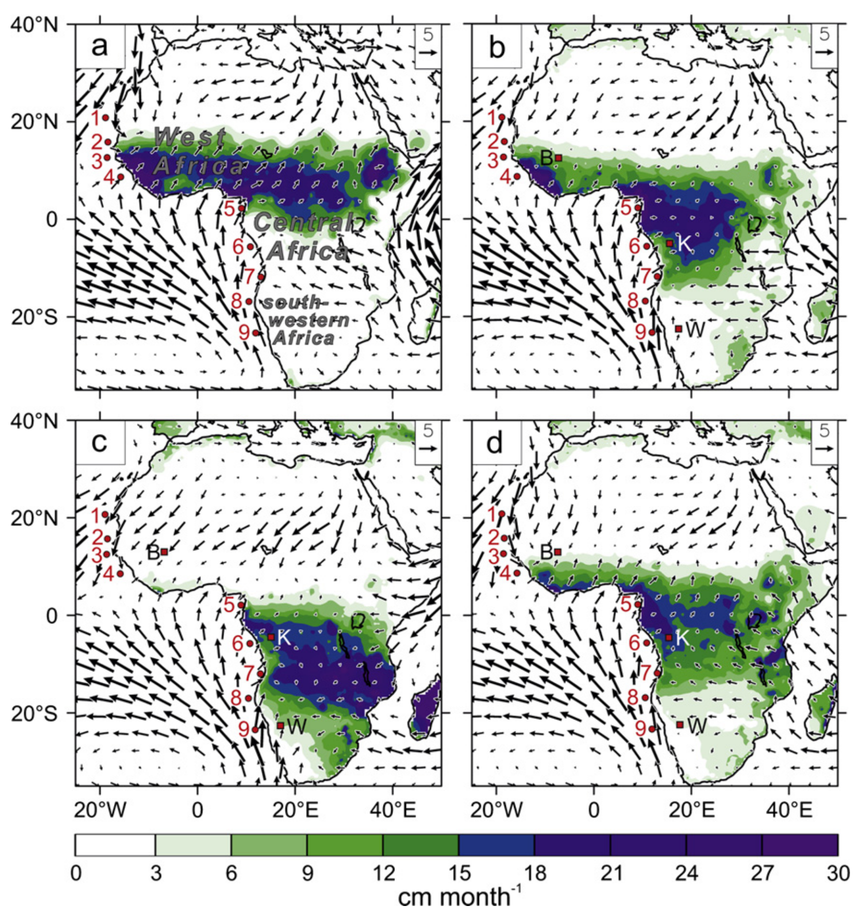

Fig. 1. Modern-day climatology of Africa, highlighting the position of the rainbelt and dominant surface wind systems during a) JJA (boreal summer), b) SON (boreal autumn), c) DJF (boreal winter) and d) MAM (boreal spring). The wind reference arrow refers to 5 m/s. Wind data are from the NCEP reanalysis (Kalnay et al., 1996) and precipitation data are from the University of Delaware dataset (climate.geog.udel.edu/~climate). Numbered red circles mark the sediment cores used in this study (Table 1). Red squares mark the three GNIP stations referred to in the text and in Fig. 2: Bamako, B; Kinshasa, K; and Windhoek, W. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)