Quaternary Science Reviews 366 (2025) 109503

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Short communication

Late Quaternary inundation and desiccation of Megalake Chad traced in dust records from the Equatorial Atlantic Ocean

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A R T I C L E I N F O

Handling editor: Mira Matthews

Keywords:
Quaternary
Holocene
Paleoclimatology
Africa
Atlantic Ocean
Radiogenic isotopes
U-Th series
Dust
Sahara
Chad

A B S T R A C T

Modern Lake Chad has shrunk in area by around 90 % since the 1960s under the twin pressures of climate change and increasing water demand. During the early to mid Holocene, the Chad basin featured a megalake with an area approximately 100 times larger than its modern remnant. In the mid/late Holocene (approximately 5000 years ago), this megalake dried out leaving behind vast deposits of readily deflated fine-grained sediments that are suggested to contribute ~25 % of the annual total global atmospheric mineral dust load. Erosion has obliterated much of the evidence of earlier North African humid periods within the Lake Chad basin, limiting our understanding of the relationship between global/regional climatology, local hydrology and dust export. Here, we present new records of thorium-normalized flux estimates of mineral dust and its radiogenic isotope composition deposited at Ocean Drilling Program Site 662, situated downwind of Megalake Chad underneath the North African winter dust plume, in the equatorial Atlantic Ocean. Our records show that sediments of the Megalake Chad basin have a distinct neodymium isotopic signature that can be traced thousands of kilometers downwind from their source when the megalake basin was dry and dust-active, whereas the fingerprint of its input was strongly suppressed at times of high lake levels. Our results show that marine sedimentary archives can preserve uninterrupted proxy records of climate-driven hydrological change on the continents, in this case, a bellwether region of Africa that features the world's most active dust source, the Bodélé Depression.

1. Introduction

Mineral dust is an active agent in the Earth system: influencing regional radiation budgets, providing nutrients to terrestrial and marine ecosystems and impacting hazardously on human health and socioeconomic infrastructure (e.g. Goudie and Middleton, 2006; Kok et al., 2023; Shao et al., 2011). Approximately half of the world's dust is produced in North Africa and half of North African dust is suggested to originate from the Bodélé Depression, making it the world's single largest source of dust (by flux) to the atmosphere (Ginoux et al., 2012; Prospero et al., 2002). Situated at the northern end of the endorheic Chad basin and lying about 155 m above sea level, the exceptional dustiness of the Bodélé Depression is controlled by two phenomena. First, the availability of thick, readily deflated deposits of lacustrine sediments left behind at the end of the most recent North African humid period (AHP) ~5 kyr ago by the desiccation of Megalake Chad, an early/mid-Holocene waterbody many times the size of the modern Lake Chad (e.g. Armitage et al., 2015; Bristow et al., 2009). Second, strong winds resulting from funnelling of the northeast trades between the Tibesti and Ennedi mountains, export dust dominantly in a southwesterly direction towards the Atlantic Ocean (Meng et al., 2017; Schepanski et al., 2009; Washington et al., 2006a, 2006b).

Spanning the boundary between the Sahara and Sahel, the Chad basin is suggested to behave as a climatological tipping point, highly

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https://doi.org/10.1016/j.quascirev.2025.109503
Received 12 March 2025; Received in revised form 23 June 2025; Accepted 23 June 2025
Available online 8 July 2025

sensitive to shifts in seasonal rainfall patterns linked to the West African monsoon (Franzke et al., 2022; Lenton et al., 2008; Washington et al., 2009). Furthermore, because the Lake Chad basin is endorheic (i.e. it has no outlet to the ocean), changes in the regional hydrological cycle drive dramatic fluctuations in the extent of Lake Chad. Ancient lake shorelines, palaeodeltas and fine-grained lacustrine sediments and diatomites reveal that much of the basin was covered by a megalake as recently as ~5 kyr ago (Drake and Bristow, 2006; Schuster et al., 2005; Swezey, 2001; Tilho, 1925). Thus, because of its location in the heart of North Africa and isolation from the ocean, the Chad basin has the potential to provide important clues on both the mechanistic forcing of past changes in rainfall climate and on the inability of most global climate models to simulate them (Brierley et al., 2020; Hopcroft and Valdes, 2021). However, the pre-Holocene climate record on land is challenging to read because of extensive erosion and dating uncertainties.

Marine sediments can provide a continuous archive of exported continental dust, allowing reconstructions of temporal variability in North African continental climate over timescales from centuries to millions of years (e.g. Adkins et al., 2006; Collins et al., 2013; Crocker et al., 2022; deMenocal, 1995; Kinsley et al., 2022; McGee et al., 2013; Mulitza et al., 2010; Palchan and Torfstein, 2019; Skonieczny et al., 2013; Tiedemann et al., 1994; Tjallingii et al., 2008). However, most published North African dust records come from core sites north of ca. 10°N, preserving records of dust dominantly sourced from northwestern Africa, whereas dust from the Bodélé Depression and the wider Lake Chad basin is mainly transported further south by the northeast trade winds, particularly during winter (Meng et al., 2017; Schepanski et al., 2009). Here, we present new records of dust flux and provenance from North Africa to the equatorial Atlantic Ocean and compare them to land-based records to develop a continuous record of Megalake Chad inundation/desiccation over the past 30 kyr.

2. Materials and methods

2.1. Study site

Ocean Drilling Program (ODP) Site 662 (1.390°S, 11.739°W, 3814 m water depth) is located on the upper eastern flank of the Mid-Atlantic Ridge, to the south of the Romanche Fracture Zone (Fig. 1). ODP Site 662 is located >700 km from the continental slope edge and is not proximal to the mouth of any major river systems. Its position on the eastern flank of the mid-Atlantic ridge protects it from riverine inputs from South America, with little influence of redistribution by bottom currents on reconstructed terrigenous fluxes (Rowland et al., 2021). Thus, terrigenous supply to ODP Site 662 is dominated by windblown dust.

ODP Site 662 sits underneath the southern route of North African dust export (Meng et al., 2017; Pokras, 1991; Schepanski et al., 2009), where strong northeasterly trade winds (the Harmattan) transport large volumes of dust from the interior of North Africa out into the Gulf of Guinea and equatorial Atlantic, particularly during boreal winter (Fig. 1, Crocker et al., 2025; Dobson and Fothergill, 1981; McTainsh, 1980; Ruddiman and Janecek, 1989; Yu et al., 2019). When the Harmattan winds reach the intertropical convergence zone (ITCZ) which occupies a southerly position during winter, dust-laden air is lofted higher into the atmosphere and can be transported westwards as far as South America (Abouchami et al., 2013; Ben-Ami et al., 2010; Prospero et al., 1981), while some of the dust load is lost from the atmosphere via wet deposition (e.g. Rowland et al., 2021; van der Does et al., 2020).

2.2. Analytical techniques

The radiogenic isotopic signature of terrigenous sediments can be an effective tracer of sediment provenance (e.g. Blanchet, 2019; Grousset and Biscaye, 2005; Scheuvens et al., 2013). Here, we present new analyses of the neodymium isotopic values (ε_{Nd}) of isolated lithogenic

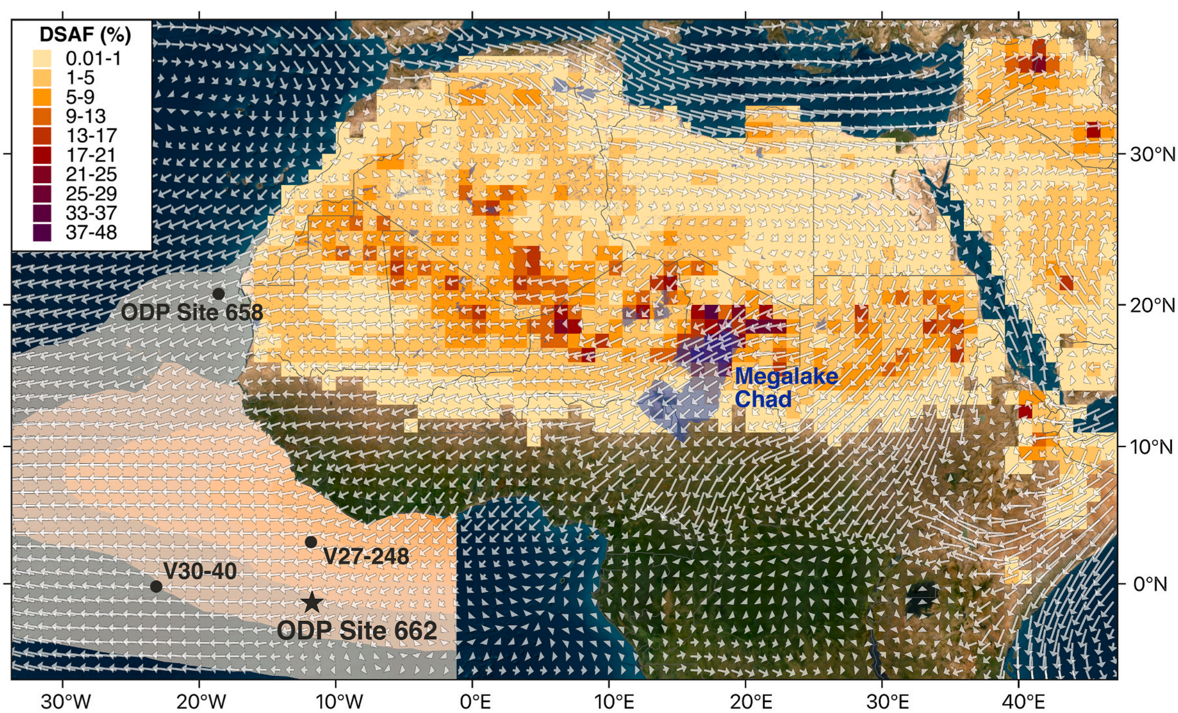

Fig. 1. Map of North African dust sources and transport pathways. Annual dust source activation frequencies (DSAF %, squares, Kunkelova et al., 2022; Kunkelova et al., 2024; Schepanski et al., 2012). Arrows indicate average 850 hPa January winds from 2010 to 2019 from ERA5 reanalysis (Hersbach et al., 2023). Winter dust over the Atlantic Ocean (pale orange) mapped by MODIS aerosol optical depth data, redrawn from Meng et al. (2017). Satellite basemap from Esri world imagery (Esri, 2023), with maximum extent of water bodies during African humid periods shown in dark blue (Manning et al., 2023). Location of ODP Site 662 marked with black star with other sites discussed shown by black dots.

fraction of sediments from ODP Site 662 (following the method of Jewell et al. (2022) to remove carbonate, organic matter, authigenic coatings, biogenic silica and marine barite). We compare these data to newly-updated dust source activation frequency (DSAF)-weighted radiogenic isotopic signatures of updated preferential dust source areas (PSAs) to reconstruct the importance of the Lake Chad basin as a dust source. We also present new thorium-normalized estimates (e.g. Adkins et al., 2006; Bacon, 1984) of dust fluxes to ODP Site 662. For full method details, see Supplementary Information (which also includes stratigraphy and supporting X-ray fluorescence and benthic oxygen isotope datasets).

3. Results and discussion

3.1. Preferential dust source areas of North Africa and their geochemical fingerprints

To provide a framework to study changes in windblown dust supply to the equatorial Atlantic Ocean, we first define new preferential dust source areas (PSAs) for North Africa. Our new PSAs (Fig. 2) and their

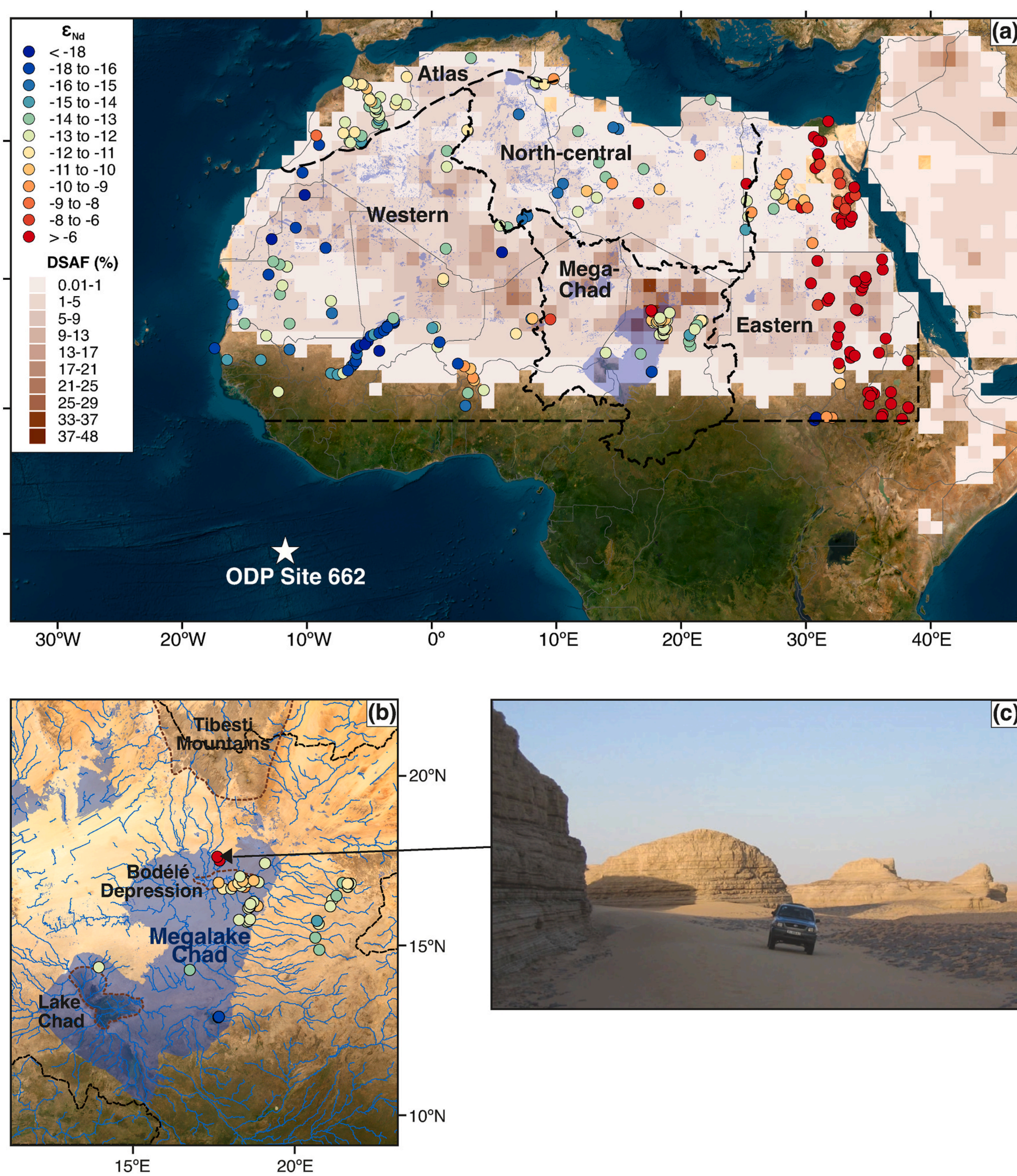

Fig. 2. Dust sources in North Africa and the Lake Chad basin. a) Map of annual dust source activation frequencies (DSAF %, brown squares, Kunkelova et al., 2022; Kunkelova et al., 2024; Schepanski et al., 2012), with coloured circles indicating neodymium isotopic compositions (ε_{Nd}) of dust-producing substrates (this study, Guinoiseau et al., 2022; Jewell et al., 2021 and references therein). Black dashed lines distinguish the five main preferential dust source areas (PSAs) shown in Table 1. Satellite basemap from Esri world imagery (Esri, 2023), with maximum extent of water bodies during African humid periods shown in dark blue (Manning et al., 2023). Location of ODP Site 662 marked with white star. b) Maximum extent of surface water bodies and palaeodrainage during past humid periods (blue) around Megalake Chad, with ε_{Nd} of dust-producing substrates superimposed using same colour scheme as panel (a). Key features marked with dashed brown lines. c) Photograph of ~10m high yardangs produced by wind erosion of Holocene sediments of the Angamma delta at the northern limit of Lake Megalake Chad, from Bristow (2023).

geochemical fingerprints (Table 1) were defined by updating the radiogenic isotope data compilation of Jewell et al. (2021) to include new and recently published data sets and by applying dust source activation frequency (DSAF) weightings (see Supplementary Information). Here, we primarily use neodymium isotope ratios (which depend strongly on bedrock geology (e.g. Bayon et al., 2015; Blanchet, 2019; Robinson et al., 2021; Scheuvens et al., 2013)) to characterise five North African PSAs. The MegaChad PSA is enclosed by the Chad basin catchment boundary and is isotopically heterogeneous, meriting further discussion.

We estimate that dust produced within the MegaChad PSA has an average ε_{Nd} value of -9.7 ± 3.9 (1 S.D.) (Table 1, Supplementary Fig. 1). The Megalake Chad basin shows a large range of isotopic signatures because the catchment is bounded to the north by, atypically for much of North Africa, young volcanic massifs such as the Tibesti (Suayah et al., 2006). Thus, sediments of Megalake Chad, and the Bodélé Depression in particular, show the influence of mixing from several isotopically distinct sediment sources (Jewell et al., 2021). Today, Lake Chad is largely fed from the southeast by the Chari River system. When past water levels were high, the Bahr el Ghazal palaeoriver system connected Lake Chad to the Bodélé Depression carrying sediments with $\varepsilon_{Nd} \approx -12$ northwards (Bristow, 2023; Jewell et al., 2021). In addition, multiple small palaeorivers flowed westwards from the Ennedi mountains, carrying relatively unradiogenic material ($\varepsilon_{Nd} \approx -12$ to -14) into the megalake (Drake et al., 2011; Jewell et al., 2021, Fig. 2b). Immediately north of the Bodélé Depression, rivers that drained the young volcanics of the Tibesti mountains during past humid intervals delivered sediments with very radiogenic ε_{Nd} signatures (ca. −3.8) to the Angamma Delta and then onwards into the Bodélé (Jewell et al., 2021). It has been suggested that these very radiogenic values are anomalous and unrepresentative of dust produced in the region (Guinoiseau et al., 2022). However, that argument is untenable because (i) annual DSAF values in this locality are the highest currently reported anywhere in North Africa (and therefore the world) (Schepanski et al., 2012, Fig. 2a) and (ii) giant yardang structures (up to 10m high) provide evidence of extensive wind-driven erosion of huge volumes of sediment from these deposits since the end of the AHP (Bristow, 2023; Bristow et al., 2009, Fig. 2c). We therefore include all ε_{Nd} values in our estimation of the signature of dust exported from the Megalake Chad basin. Our estimate for the MegaChad PSA is in good agreement with the most radiogenic ε_{Nd} values recorded in African dust reaching the Amazon (−9.9, Barkley et al., 2022) and a dust trap sample taken within the Bodélé Depression (−10.7, Guinoiseau et al., 2022).

3.2. Windblown dust supplied to the equatorial Atlantic Ocean provides a proxy record of inundation/desiccation of Megalake Chad

ODP Site 662 sits directly downwind from the remnants of Megalake Chad (including the Bodélé Depression, the most dust-active location in North Africa) (Fig. 1). ε_{Nd} values of the terrigenous fraction at ODP Site 662 over the past 30 kyr range between −11.1 and −12.9 (Fig. 3f). We therefore interpret this result to represent mixing between the highly dust active Megachad PSA (ε_{Nd} = -9.7 ± 3.9) and the more proximal Western PSA (ε_{Nd} = -14.4 ± 3.1) (Table 1). We do not rule out minor contributions from the North-central, Atlas or Eastern PSAs, but these regions are unlikely to be major sources of terrigenous material to ODP Site 662 because of their lower DSAFs, long transport distances to the Equatorial Atlantic Ocean and less favourable prevailing winds (Fig. 1) (Schepanski et al., 2009, 2017; Washington et al., 2003).

The onset of humid conditions across North Africa associated with the Holocene AHP drove a major increase in the number of dated lacustrine deposits across the Lake Chad basin from ~13 ka, which peaked from 10 to 8 ka (Fig. 3; Lézine et al., 2011). Water levels in the Bodélé basin reached a highstand by ~11.5 ka, connecting it with Lake Chad to the south to form a megalake (Armitage et al., 2015). A single data point from the Bodélé basin dated to 13.5 ka suggests there may have been sporadic earlier wet intervals, but the main interval of humidity occurred between ca. 11 and 5 ka. Dust fluxes recorded at ODP

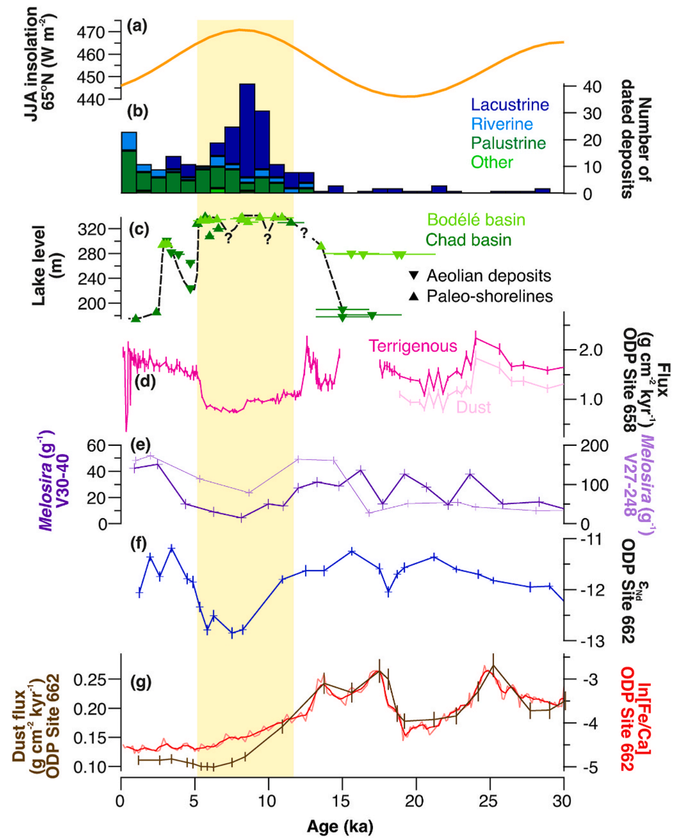

Fig. 3. Megalake Chad and regional climate reconstructions over the past 30 kyr. Yellow shading indicates the timing of the African Humid Period in the Megalake Chad basin. a) Summer (June-July-August) insolation at 65°N from the La2004 orbital solution (orange) (Laskar et al., 2004). b) Age distribution of dated waterlain sediments from within the Megalake Chad basin (Lézine et al., 2011; Manning et al., 2023). c) Reconstructed water levels (black dashed line) of the Chad Basin (dark green) and Bodélé Basin (light green) estimated from aeolian deposits above the water level (inverted triangles) and paleo-shorelines (triangles), redrawn from Armitage et al. (2015). d) Terrigenous (dark pink) and dust (light pink) fluxes from ODP Site 658 with 1σ uncertainty shown by vertical bars (Adkins et al., 2006; Kinsley et al., 2022). e) Concentration of freshwater diatom genus Melosira in marine sediment cores V30-40 (dark purple) and V27-248 (light purple) (Pokras and Mix, 1985). Site locations shown on Fig. 1. f) ε_{Nd} of the bulk lithogenic fraction of ODP Site 662 sediments. g) Dust flux at ODP Site 662 (brown) with vertical bars indicating 1 uncertainty and ln[Fe/Ca] of XRF core scanning elemental counts (red), with darker colour indicating 5-pt running mean. New data available in Supplementary Table 2.

Table 1
Radiogenic isotope signatures of North African dust Preferential Source Areas (PSAs). S.D. = standard deviation, n = number of samples included. Data sources: (Abouchami et al., 2013; Bayon et al., 2024; Fielding et al., 2017; Garzanti et al., 2015; Gross et al., 2016; Grousset and Biscaye, 2005; Grousset et al., 1998; Grousset et al., 1992; Guinoiseau et al., 2022; Jewell et al., 2021; Krom et al., 1999; Kumar et al., 2014; Padoan et al., 2011; Revel et al., 2010; van der Does et al., 2018; Zhao et al., 2018 and this study).

PSA name	ε_{Nd}	1 S.D.	n	$^{87}Sr/^{86}Sr$	1 S.D.	n
Western	−14.4	3.1	67	0.7268	0.0083	39
Atlas	−12.8	1.7	41	0.7258	0.0024	34
MegaChad	−9.7	3.9	52	0.7168	0.0054	32
North-central	−12.5	2.9	28	0.7139	0.0082	13
Eastern	−1.7	3.6	61	0.7065	0.0020	39

Site 662 decreased by more than a factor of two (from 0.24 to 0.1 g cm^{-2} kyr^{-1}) between ~13.5 ka and 8.5 ka, coincident with a shift in ε_{Nd} values from −11.8 to −12.8 (Fig. 3). We attribute this shift in dust provenance to the formation of Megalake Chad during the AHP which shut down dust production in the world's most active hotspot, driving a decrease in the supply of radiogenic dust to the equatorial Atlantic and a shift in our ODP Site 662 record towards the more unradiogenic average compositions of the Western North Africa PSA. We favour this explanation over shifting wind patterns, in agreement with model simulations which suggest that wind directions remained largely unchanged (e.g. Braconnot et al., 2000; Murphy et al., 2014; Zhao and Harrison, 2012), and with the stable palaeowind fields documented further north along the African margin (Cole et al., 2009; Crocker et al., 2022; Hooghiemstra et al., 1987).

From ~6 to 4 ka, the radiogenic isotope signature recorded at ODP Site 662 shifted back to pre-AHP ε_{Nd} values of −12 to −11. At approximately the same time, lake levels fell rapidly across the Chad basin (Armitage et al., 2015; Kröpelin et al., 2008), with an increase in freshwater diatom fossils deflated from the exposed lake beds recorded in Atlantic Ocean sediments (Pokras and Mix, 1985) (Fig. 3e). We therefore propose that shifts in the provenance of dust (revealed by its neodymium isotope signature) preserved in marine sediments situated underneath the pathway of the winter dust plume can be used as a proxy means of tracking past inundation/desiccation of Megalake Chad on geological timescales.

3.3. Decoupling of dust flux and provenance during Heinrich stadials and the late Holocene

Combined analysis of neodymium isotope measurements and thorium-normalized dust fluxes reveals broadly similar trends in these two proxies, particularly between 20 and 5 ka. However, there are also examples of decoupled proxy behaviour. One example occurs at the end of the AHP, when large-scale desiccation of Megalake Chad induced a marked shift towards more radiogenic ε_{Nd} values at ODP Site 662 but we document only a slight increase in dust fluxes (Fig. 3). This modest increase in dust fluxes at ODP Site 662 contrasts with the pronounced end-AHP increase in dust fluxes recorded at more northerly sites (e.g. ODP Site 658, Fig. 3d; Adkins et al., 2006; Kinsley et al., 2022). However, it is consistent with records from other (winter dust plume influenced) equatorial sites stretching across the Atlantic Ocean (Supplementary Fig. 2; Bradtmiller et al., 2007; Francois et al., 1990; Lippold et al., 2016; Ng et al., 2018; Rowland et al., 2021). The low late Holocene dust fluxes recorded across the equatorial Atlantic could be explained by precipitation-induced dust scavenging (e.g. McGee et al., 2007; Rowland et al., 2021; Skinner and Poulsen, 2016; Tiwari et al., 2023). This explanation is consistent with the observation that, even today, the tropical rainbelt lies north of ODP Site 662 during boreal winter despite having shifted/contracted southwards from its mid-Holocene position in response to decreasing northern hemisphere insolation (Collins et al., 2011; Shanahan et al., 2015; Singarayer and Burrough, 2015).

A second example of decoupled proxy behaviour comes from the stadial conditions of the last glacial, when sea surface temperatures in the North Atlantic Ocean were especially cold. During these intervals, very dusty conditions are documented in northwest Africa and attributed both to a strengthening of the northeasterly trade winds (Kinsley et al., 2022; Middleton et al., 2018; Murphy et al., 2014) and a decrease in tropical soil moisture with a proposed ~6° southward shift in the Sahara-Sahel boundary (Collins et al., 2013; Hopcroft et al., 2023; Mulitza et al., 2008). Our records provide a test of these hypotheses because modern Lake Chad lies at approximately the same latitude as the suggested southern limit of the Saharan desert during Heinrich stadials (13 ± 3°N, Collins et al., 2013) and the most southerly identified Saharan fossilised sand dunes (14°N, Grove, 1958; Michel and Michel, 1973). Our dust flux and ln[Fe/Ca] records from ODP Site 662 take a similar form to records from further north (e.g. ODP Site 658), with peaks in dust flux and ln[Fe/Ca] (indicating a high proportion of terrigenous material) at ca. 24.7, 17.3 and 13.5 ka, with ages approximately corresponding to Heinrich stadial 2, Heinrich stadial 1 and the Younger Dryas respectively (Fig. 3). However, there is no strong evidence of a shift in ε_{Nd} values across these events to indicate a major change in the location of active dust sources at these times. This result implies that many of the desiccated water bodies that act as key dust source hotspots today (Bakker et al., 2019; Prospero et al., 2002; Washington et al., 2003) were already at least seasonally dry and dust-active under baseline glacial conditions. Thus, any further decreases in soil moisture and/or increases in wind strength associated with cold North Atlantic sea surface temperatures (e.g. Hopcroft et al., 2023; Shanahan et al., 2012; Weldeab et al., 2007) did not have a major influence on the spatial distribution of dust sources. In this interpretation, the increase in dust flux recorded at ODP 662 was driven by a combination of increased soil erodibility and a strengthening of northeasterly winds during stadial periods (and/or increase in gustiness) (Kinsley et al., 2022; Liu et al., 2014; McGee et al., 2010; Murphy et al., 2014), resulting in greater deflation of existing dust sources and export to the eastern equatorial Atlantic.

4. Summary and conclusions

The detrital fraction of equatorial Atlantic sediments from ODP Site 662 provides a continuous record of windblown dust from North Africa and its neodymium isotopic signature preserves a proxy record of the inundation/desiccation of the endorheic Lake Chad basin. The Bodélé Depression, the dustiest place on Earth, has a comparatively radiogenic neodymium isotope signature for western/central North Africa because of riverine input of fine-grained sediments from the young volcanic Tibesti Mountains during past intervals of humidity. When the Lake Chad basin is arid, dust fluxes from the basin are high, with a radiogenic neodymium isotope signature imprinted onto windblown dust exported to the eastern equatorial Atlantic by strong northeasterly trade winds. During the mid-Holocene African humid period, when a megalake occupied much of the Lake Chad basin, we record a shift to more unradiogenic isotope values and low Th-normalized dust fluxes signalling a shutdown of the main dust sources in the Lake Chad basin. Our approach of combining analysis of neodymium isotopes and dust fluxes allows us to separate out the influences of transport processes and sediment availability driven by regional hydroclimate on the export of aeolian sediments from the dustiest place on Earth using continuous sedimentary archives which have the potential to preserve records over thousands to millions of years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded through National Environment Research Council (NERC) Standard Grant NE/X000869/1 (PAW and CX), with additional funding from Royal Society Challenge Grant CHG/R1/170054 (PAW) and University of Southampton's GCRF strategic development fund grant 519016 (PAW and AJC), a NERC studentship to AMJ (NE/L002531/1) and QRA-14CHRONO Centre Radiocarbon Dating Awards to WRCB and ALM. Research by PSB, KM and ND utilised in this paper was funded by the Leverhulme Trust (grants RPG-2016-115 & ECF-2019-538). We are grateful to Tim Herbert and Alan Mix for providing *C. wuellerstorfi* δ^{18}O and *Melosira* spp. concentration data respectively. We thank B. Hambach, M. Wilding, J. A. Milton, A. Gale and V. Lukies for analytical assistance and H. Kuhlman and A. Wülbers of the Bremen Core Repository. Peter Hopcroft, Kerstin Schepanski, Thomas Westerhold, Ulla Röhl, Tereza Kunkelova and Yuxi Jin are thanked for discussions that helped to improve this manuscript. This research used samples provided by (I)ODP, which was sponsored by the US National Science Foundation and participating countries under management of Joint Oceanographic Institutions, Inc. We thank Adi Torfstein and one anonymous reviewer for their constructive feedback which helped to improve this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2025.109503.

Data availability

All new data published in this study and compiled radiogenic isotope data are available as supplementary data files and at https://doi.org/10.5281/zenodo.14795870.

References

Abouchami, W., Näthe, K., Kumar, A., Galer, S.J.G., Jochum, K.P., Williams, E., Horbe, A.M.C., Rosa, J.W.C., Balsam, W., Adams, D., Mezger, K., Andreae, M.O., 2013. Geochemical and isotopic characterization of the Bodélé Depression dust source and implications for transatlantic dust transport to the Amazon Basin. Earth Planet Sci. Lett. 380, 112–123.

Adkins, J., deMenocal, P., Eshel, G., 2006. The "African humid period" and the record of marine upwelling from excess 230Th in Ocean Drilling Program Hole 658C. Paleoceanography 21, PA4203.

Armitage, S.J., Bristow, C.S., Drake, N.A., 2015. West African monsoon dynamics inferred from abrupt fluctuations of Lake Mega-Chad. Proc. Natl. Acad. Sci. 112, 8543–8548.

Bacon, M.P., 1984. Glacial to interglacial changes in carbonate and clay sedimentation in the Atlantic Ocean estimated from 230Th measurements. Chem. Geol. 46, 97–111.

Bakker, N.L., Drake, N.A., Bristow, C.S., 2019. Evaluating the relative importance of northern African mineral dust sources using remote sensing. Atmos. Chem. Phys. 19, 10525–10535.

Barkley, A.E., Pourmand, A., Longman, J., Sharifi, A., Prospero, J.M., Panechou, K., Bakker, N., Drake, N., Guinoiseau, D., Gaston, C.J., 2022. Interannual variability in the source location of North African dust transported to the Amazon. Geophys. Res. Lett. 49, e2021GL097344.

Bayon, G., Garzanti, E., Dinis, P., Beaufort, D., Barrat, J.-A., Germain, Y., Trinquier, A., Barbarano, M., Overare, B., Adeaga, O., Braquet, N., 2024. Contribution of Saharan dust to chemical weathering fluxes and associated phosphate release in West Africa. Earth Planet Sci. Lett. 641, 118845.

Bayon, G., Toucanne, S., Skonieczny, C., André, L., Bermell, S., Cheron, S., Dennielou, B., Etoubleau, J., Freslon, N., Gauchery, T., Germain, Y., Jorry, S.J., Ménot, G., Monin, L., Ponzevera, E., Rouget, M.L., Tachikawa, K., Barrat, J.A., 2015. Rare earth elements and neodymium isotopes in world river sediments revisited. Geochem. Cosmochim. Acta 170, 17–38.

Ben-Ami, Y., Koren, I., Rudich, Y., Artaxo, P., Martin, S.T., Andreae, M.O., 2010. Transport of North African dust from the Bodélé depression to the Amazon basin: a case study. Atmos. Chem. Phys. 10, 7533–7544.

Blanchet, C.L., 2019. A database of marine and terrestrial radiogenic Nd and Sr isotopes for tracing earth-surface processes. Earth Syst. Sci. Data 11, 741–759.

Braconnot, P., Joussaume, S., de Noblet, N., Ramstein, G., 2000. Mid-holocene and last glacial maximum African monsoon changes as simulated within the Paleoclimate modelling intercomparison Project. Global Planet. Change 26, 51–66.

Bradtmiller, L.I., Anderson, R.F., Fleisher, M.Q., Burckle, L.H., 2007. Opal burial in the equatorial Atlantic Ocean over the last 30 ka: implications for glacial-interglacial changes in the ocean silicon cycle. Paleoceanography 22.

Brierley, C.M., Zhao, A., Harrison, S.P., Braconnot, P., Williams, C.J.R., Thornalley, D.J.R., Shi, X., Peterschmitt, J.Y., Ohgaito, R., Kaufman, D.S., Kageyama, M., Hargreaves, J.C., Erb, M.P., Emile-Geay, J., D'Agostino, R., Chandan, D., Carré, M., Bartlein, P.J., Zheng, W., Zhang, Z., Zhang, Q., Yang, H., Volodin, E.M., Tomas, R.A., Routson, C., Peltier, W.R., Otto-Bliesner, B., Morozova, P.A., McKay, N.P., Lohmann, G., Legrande, A.N., Guo, C., Cao, J., Brady, E., Annan, J.D., Abe-Ouchi, A., 2020. Large-scale features and evaluation of the PMIP4-CMIP6 midHolocene simulations. Clim. Past 16, 1847–1872.

Bristow, C.S., 2023. Geomorphology of the Bodélé depression: the dustiest place on earth. In: Knight, J., Merlo, S., Zerboni, A. (Eds.), Landscapes and Landforms of the Central Sahara. Springer International Publishing, Cham, pp. 121–129.

Bristow, C.S., Drake, N., Armitage, S., 2009. Deflation in the dustiest place on earth: the Bodélé depression, Chad. Geomorphology 105, 50–58.

Cole, J.M., Goldstein, S.L., deMenocal, P.B., Hemming, S.R., Grousset, F.E., 2009. Contrasting compositions of Saharan dust in the eastern Atlantic Ocean during the last deglaciation and African Humid Period. Earth Planet Sci. Lett. 278, 257–266.

Collins, J.A., Govin, A., Mulitza, S., Heslop, D., Zabel, M., Hartmann, J., Roehl, U., Wefer, G., 2013. Abrupt shifts of the Sahara-Sahel boundary during Heinrich stadials. Clim. Past 9, 1181–1191.

Collins, J.A., Schefuß, E., Heslop, D., Mulitza, S., Prange, M., Zabel, M., Tjallingii, R., Dokken, T.M., Huang, E., Mackensen, A., Schulz, M., Tian, J., Zarriess, M., Wefer, G., 2011. Interhemispheric symmetry of the tropical African rainbelt over the past 23,000 years. Nat. Geosci. 4, 42–45.

Crocker, A.J., Jewell, A.M., Mitsunaga, B.A., Buchanan, S., Brombacher, A., Hambach, B., Wilding, M.R., Westerhold, T., Röhl, U., Russell, J.M., Herbert, T.D., Xuan, C., Wilson, P.A., 2025. Increased North African dust fluxes and higher productivity in the eastern equatorial Atlantic Ocean linked to stronger trade winds from about 2.7 million years ago. Paleoceanogr. Paleoclimatol. 40, e2024PA004891.

Crocker, A.J., Naafs, B.D.A., Westerhold, T., James, R.H., Cooper, M.J., Röhl, U., Pancost, R.D., Xuan, C., Osborne, C.P., Beerling, D.J., Wilson, P.A., 2022. Astronomically controlled aridity in the Sahara since at least 11 million years ago. Nat. Geosci. 15, 671–676.

deMenocal, P.B., 1995. Plio-pleistocene African climate. Science 270, 53–59.

Dobson, M., Fothergill, J., 1981. IV. An account of the Harmattan, a singular African wind. Phil. Trans. Roy. Soc. Lond. 71, 46–57.

Drake, N., Bristow, C., 2006. Shorelines in the Sahara: geomorphological evidence for an enhanced monsoon from palaeolake Megachad. Holocene 16, 901–911.

Drake, N.A., Blench, R.M., Armitage, S.J., Bristow, C.S., White, K.H., 2011. Ancient watercourses and biogeography of the Sahara explain the peopling of the desert. Proc. Natl. Acad. Sci. 108, 458–462.

Esri, D., 2023. IGN, IGP, swisstopo, and the GIS user community. ESRI World Imagery. GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid.

Fielding, L., Najman, Y., Millar, I., Butterworth, P., Ando, S., Padoan, M., Barfod, D., Kneller, B., 2017. A detrital record of the Nile River and its catchment. J. Geol. Soc. 174, 301–317.

Francois, R., Bacon, M.P., Suman, D.O., 1990. Thorium 230 profiling in deep-sea sediments: high-resolution records of flux and dissolution of carbonate in the equatorial Atlantic during the last 24,000 years. Paleoceanography 5, 761–787.

Franzke, C.L., Ciullo, A., Gilmore, E.A., Matias, D.M., Nagabhatla, N., Orlov, A., Paterson, S.K., Scheffran, J., Sillmann, J., 2022. Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling. Environ. Res. Lett. 17, 015004.

Garzanti, E., Andò, S., Padoan, M., Vezzoli, G., El Kammar, A., 2015. The modern Nile sediment system: processes and products. Quat. Sci. Rev. 130, 9–56.

Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., Zhao, M., 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys. 50, RG3005.

Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, Berlin, Heidelberg.

Gross, A., Palchan, D., Krom, M.D., Angert, A., 2016. Elemental and isotopic composition of surface soils from key Saharan dust sources. Chem. Geol. 442, 54–61.

Grousset, F.E., Biscaye, P.E., 2005. Tracing dust sources and transport patterns using Sr, Nd and Pb isotopes. Chem. Geol. 222, 149–167.

Grousset, F.E., Parra, M., Bory, A., Martinez, P., Bertrand, P., Shimmield, G., Ellam, R.M., 1998. Saharan wind regimes traced by the Sr–Nd isotopic composition of subtropical Atlantic sediments: last Glacial Maximum vs today. Quat. Sci. Rev. 17, 395–409.

Grousset, F.E., Rognon, P., Coudé-Gaussen, G., Pédemay, P., 1992. Origins of peri-Saharan dust deposits traced by their Nd and Sr isotopic composition. Palaeogeogr. Palaeoclimatol. Palaeoecol. 93, 203–212.

Grove, A.T., 1958. The ancient Erg of Hausaland, and similar formations on the south side of the Sahara. Geogr. J. 124, 528–533.

Guinoiseau, D., Singh, S.P., Galer, S.J.G., Abouchami, W., Bhattacharyya, R., Kandler, K., Bristow, C., Andreae, M.O., 2022. Characterization of Saharan and Sahelian dust sources based on geochemical and radiogenic isotope signatures. Quat. Sci. Rev. 293, 107729.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N., 2023. ERA5 monthly averaged data on pressure levels from 1940 to present. In: C3S), C.C.C.S. (Ed.), Climate Data Store (CDS).

Hooghiemstra, H., Bechler, A., Beug, H.-J., 1987. Isopollen maps for 18,000 years B.P. of the Atlantic offshore of northwest Africa: evidence for paleowind circulation. Paleoceanography 2, 561–582.

Hopcroft, P.O., Pichat, S., Valdes, P.J., Kienast, S.S., 2023. Sensitivity of the tropical dust cycle to glacial abrupt climate changes. Geophys. Res. Lett. 50, e2022GL101197.

Hopcroft, P.O., Valdes, P.J., 2021. Paleoclimate-conditioning Reveals a North Africa Land–Atmosphere Tipping Point, vol 118. Proceedings of the National Academy of Sciences, e2108783118.

Jewell, A.M., Cooper, M.J., Milton, J.A., James, R.H., Crocker, A.J., Wilson, P.A., 2022. Chemical isolation and isotopic analysis of terrigenous sediments with emphasis on effective removal of contaminating marine phases including barite. Chem. Geol. 589, 120673.

Jewell, A.M., Drake, N., Crocker, A.J., Bakker, N.L., Kunkelova, T., Bristow, C.S., Cooper, M.J., Milton, J.A., Breeze, P.S., Wilson, P.A., 2021. Three North African dust source areas and their geochemical fingerprint. Earth Planet Sci. Lett. 554, 116645.

Kinsley, C.W., Bradtmiller, L.I., McGee, D., Galgay, M., Stuut, J.-B., Tjallingii, R., Winckler, G., deMenocal, P.B., 2022. Orbital- and millennial-scale variability in northwest African dust emissions over the past 67,000 years. Paleoceanogr. Paleoclimatol. 36, e2020PA004137.

Kok, J.F., Storelvmo, T., Karydis, V.A., Adebiyi, A.A., Mahowald, N.M., Evan, A.T., He, C., Leung, D.M., 2023. Mineral dust aerosol impacts on global climate and climate change. Nat. Rev. Earth Environ.

Krom, M.D., Cliff, R.A., Eijsink, L.M., Herut, B., Chester, R., 1999. The characterisation of Saharan dusts and Nile particulate matter in surface sediments from the Levantine basin using Sr isotopes. Mar. Geol. 155, 319–330.

Kröpelin, S., Verschuren, D., Lézine, A.-M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J.-P., Fagot, M., Rumes, B., Russell, J.M., Darius, F., Conley, D.J., Schuster, M., von Suchodoletz, H., Engstrom, D.R., 2008. Climate-driven ecosystem succession in the Sahara: the past 6000 years. Science 320, 765–768.
Kumar, A., Abouchami, W., Galer, S.J.G., Garrison, V.H., Williams, E., Andreae, M.O., 2014. A radiogenic isotope tracer study of transatlantic dust transport from Africa to the Caribbean. Atmos. Environ. 82, 130–143.
Kunkelova, T., Crocker, A.J., Jewell, A.M., Breeze, P.S., Drake, N.A., Cooper, M.J., Milton, J.A., Hennen, M., Shahgedanova, M., Petraglia, M., Wilson, P.A., 2022. Dust sources in Westernmost Asia are geochemically distinct from those of the Eastern Sahara. Quat. Sci. Rev. 294, 107717.
Kunkelova, T., Crocker, A.J., Wilson, P.A., Schepanski, K., 2024. Dust source activation frequency in the Horn of Africa. J. Geophys. Res. Atmos. 129, e2023JD039694.
Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285.
Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. 105, 1786–1793.
Lézine, A.-M., Hély, C., Grenier, C., Braconnot, P., Krinner, G., 2011. Sahara and Sahel vulnerability to climate changes, lessons from Holocene hydrological data. Quat. Sci. Rev. 30, 3001–3012.
Lippold, J., Gutjahr, M., Blaser, P., Christner, E., de Carvalho Ferreira, M.L., Mulitza, S., Christl, M., Wombacher, F., Böhm, E., Antz, B., Cartapanis, O., Vogel, H., Jaccard, S. L., 2016. Deep water provenance and dynamics of the (de)glacial Atlantic meridional overturning circulation. Earth Planet Sci. Lett. 445, 68–78.
Liu, Y., Chiang, J.C.H., Chou, C., Patricola, C.M., 2014. Atmospheric teleconnection mechanisms of extratropical North Atlantic SST influence on Sahel rainfall. Clim. Dyn. 43, 2797–2811.
Manning, K., Breeze, P.S., Drake, N., Dunne, J., Casanova, E., Evershed, R.P., 2023. Habitat fragmentation and the sporadic spread of pastoralism in the mid-Holocene Sahara. Quat. Sci. Rev. 309, 108070.
McGee, D., Broecker, W.S., Winckler, G., 2010. Gustiness: the driver of glacial dustiness? Quat. Sci. Rev. 29, 2340–2350.
McGee, D., deMenocal, P.B., Winckler, G., Stuut, J.B.W., Bradtmiller, L.I., 2013. The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000 yr. Earth Planet Sci. Lett. 371–372, 163–176.
McGee, D., Marcantonio, F., Lynch-Stieglitz, J., 2007. Deglacial changes in dust flux in the eastern equatorial Pacific. Earth Planet Sci. Lett. 257, 215–230.
McTainsh, G., 1980. Harmattan dust deposition in northern Nigeria. Nature 286, 587–588.
Meng, L., Gao, H.W., Yu, Y., Yao, X.H., Gao, Y., Zhang, C., Fan, L., 2017. A new approach developed to study variability in North African dust transport routes over the Atlantic during 2001–2015. Geophys. Res. Lett. 44 (10), 026-010,035.
Michel, P., Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie: étude géomorphologique. Orstom, Paris, England.
Middleton, J.L., Mukhopadhyay, S., Langmuir, C.H., McManus, J.F., Huybers, P.J., 2018. Millennial-scale variations in dustiness recorded in Mid-Atlantic sediments from 0 to 70 ka. Earth Planet Sci. Lett. 482, 12–22.
Mulitza, S., Heslop, D., Pittauerova, D., Fischer, H.W., Meyer, I., Stuut, J.-B., Zabel, M., Mollenhauer, G., Collins, J.A., Kuhnert, H., Schulz, M., 2010. Increase in African dust flux at the onset of commercial agriculture in the Sahel region. Nature 466, 226–228.
Mulitza, S., Prange, M., Stuut, J.-B., Zabel, M., von Dobeneck, T., Itambi, A.C., Nizou, J., Schulz, M., Wefer, G., 2008. Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning. Paleoceanography 23, PA4206.
Murphy, L.N., Clement, A.C., Albani, S., Mahowald, N.M., Swart, P., Arienzo, M.M., 2014. Simulated changes in atmospheric dust in response to a Heinrich stadial. Paleoceanography 29, 30–43.
Ng, H.C., Robinson, L.F., McManus, J.F., Mohamed, K.J., Jacobel, A.W., Ivanovic, R.F., Gregoire, L.J., Chen, T., 2018. Coherent deglacial changes in western Atlantic Ocean circulation. Nat. Commun. 9, 2947.
Padoan, M., Garzanti, E., Harlavan, Y., Villa, I.M., 2011. Tracing Nile sediment sources by Sr and Nd isotope signatures (Uganda, Ethiopia, Sudan). Geochem. Cosmochim. Acta 75, 3627–3644.
Palchan, D., Torfstein, A., 2019. A drop in Sahara dust fluxes records the northern limits of the African Humid Period. Nat. Commun. 10, 3803.
Pokras, E.M., 1991. Source areas and transport mechanisms for freshwater and brackish-water diatoms deposited in pelagic sediments of the equatorial Atlantic. Quat. Res. 35, 144–156.
Pokras, E.M., Mix, A.C., 1985. Eolian evidence for spatial variability of late quaternary climates in tropical Africa. Quat. Res. 24, 137–149.
Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., Gill, T.E.C., 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Rev. Geophys. 40, 2–31, 2-1.
Prospero, J.M., Glaccum, R.A., Nees, R.T., 1981. Atmospheric transport of soil dust from Africa to South America. Nature 289, 570–572.
Revel, M., Ducassou, E., Grousset, F.E., Bernasconi, S.M., Migeon, S., Revillon, S., Mascle, J., Murat, A., Zaragosi, S., Bosch, D., 2010. 100,000 Years of African monsoon variability recorded in sediments of the Nile margin. Quat. Sci. Rev. 29, 1342–1362.
Robinson, S., Ivanovic, R., van de Flierdt, T., Blanchet, C.L., Tachikawa, K., Martin, E.E., Cook, C.P., Williams, T., Gregoire, L., Plancherel, Y., Jeandel, C., Arsouze, T., 2021. Global continental and marine detrital εNd: an updated compilation for use in understanding marine Nd cycling. Chem. Geol., 120119
Rowland, G.H., Robinson, L.F., Hendry, K.R., Ng, H.C., McGee, D., McManus, J.F., 2021. The spatial distribution of aeolian dust and terrigenous fluxes in the tropical Atlantic Ocean since the last glacial maximum. Paleoceanogr. Paleoclimatol. 36, e2020PA004148.
Ruddiman, W., Janecek, T., 1989. Pliocene-Pleistocene biogenic and terrigenous fluxes at equatorial Atlantic Sites 662, 663, and 664. Proc. Ocean Drill. Progr. Sci. Results 1–240.
Schepanski, K., Heinold, B., Tegen, I., 2017. Harmattan, Saharan heat low, and West African monsoon circulation: modulations on the Saharan dust outflow towards the North Atlantic. Atmos. Chem. Phys. 17, 10223–10243.
Schepanski, K., Tegen, I., Macke, A., 2009. Saharan dust transport and deposition towards the tropical northern Atlantic. Atmos. Chem. Phys. 9, 1173–1189.
Schepanski, K., Tegen, I., Macke, A., 2012. Comparison of satellite based observations of Saharan dust source areas. Rem. Sens. Environ. 123, 90–97.
Scheuvens, D., Schütz, L., Kandler, K., Ebert, M., Weinbruch, S., 2013. Bulk composition of northern African dust and its source sediments — a compilation. Earth Sci. Rev. 116, 170–194.
Schuster, M., Roquin, C., Duringer, P., Brunet, M., Caugy, M., Fontugne, M., Taïsso Mackaye, H., Vignaud, P., Ghienne, J.-F., 2005. Holocene Lake Mega-Chad palaeoshorelines from space. Quat. Sci. Rev. 24, 1821–1827.
Shanahan, T.M., Beck, J.W., Overpeck, J.T., McKay, N.P., Pigati, J.S., Peck, J.A., Scholz, C.A., Heil, C.W., King, J., 2012. Late Quaternary sedimentological and climate changes at Lake Bosumtwi Ghana: new constraints from laminae analysis and radiocarbon age modeling. Palaeogeogr. Palaeoclimatol. Palaeoecol. 361–362, 49–60.
Shanahan, T.M., McKay, N.P., Hughen, K.A., Overpeck, J.T., Otto-Bliesner, B., Heil, C.W., King, J., Scholz, C.A., Peck, J., 2015. The time-transgressive termination of the African Humid Period. Nat. Geosci. 8 (2), 140–144.
Shao, Y., Wyrwoll, K.-H., Chappell, A., Huang, J., Lin, Z., McTainsh, G.H., Mikami, M., Tanaka, T.Y., Wang, X., Yoon, S., 2011. Dust cycle: an emerging core theme in Earth system science. Aeolian Res. 2, 181–204.
Singarayer, J.S., Burrough, S.L., 2015. Interhemispheric dynamics of the African rainbelt during the late Quaternary. Quat. Sci. Rev. 124, 48–67.
Skinner, C.B., Poulsen, C.J., 2016. The role of fall season tropical plumes in enhancing Saharan rainfall during the African Humid Period. Geophys. Res. Lett. 43, 349–358.
Skonieczny, C., Bory, A., Bout-Roumazeilles, V., Abouchami, W., Galer, S.J.G., Crosta, X., Diallo, A., Ndiaye, T., 2013. A three-year time series of mineral dust deposits on the West African margin: sedimentological and geochemical signatures and implications for interpretation of marine paleo-dust records. Earth Planet Sci. Lett. 364, 145–156.
Suayah, I.B., Miller, J.S., Miller, B.V., Bayer, T.M., Rogers, J.J., 2006. Tectonic significance of Late Neoproterozoic granites from the Tibesti massif in southern Libya inferred from Sr and Nd isotopes and U–Pb zircon data. J. Afr. Earth Sci. 44, 561–570.
Swezey, C., 2001. Eolian sediment responses to late Quaternary climate changes: temporal and spatial patterns in the Sahara. Palaeogeogr. Palaeoclimatol. Palaeoecol. 167, 119–155.
Tiedemann, R., Sarnthein, M., Shackleton, N.J., 1994. Astronomic timescale for the Pliocene Atlantic δ18O and dust flux records of Ocean Drilling Program site 659. Paleoceanography 9, 619–638.
Tilho, J., 1925. Sur l'aire probable d'extension maxima de la mer paléotchadienne. CR Acad. Sci. Paris 181, 643–646.
Tiwari, S., Ramos, R.D., Pausata, F.S.R., LeGrande, A.N., Griffiths, M.L., Beltrami, H., Wainer, I., de Vernal, A., Litchmore, D.T., Chandan, D., Peltier, W.R., Tabor, C.R., 2023. On the remote impacts of mid-Holocene Saharan vegetation on south American hydroclimate: a modeling intercomparison. Geophys. Res. Lett. 50, e2022GL101974.
Tjallingii, R., Claussen, M., Stuut, J.-B.W., Fohlmeister, J., Jahn, A., Bickert, T., Lamy, F., Rohl, U., 2008. Coherent high- and low-latitude control of the northwest African hydrological balance. Nat. Geosci. 1, 670–675.
van der Does, M., Brummer, G.-J.A., van Crimpen, F.C.J., Korte, L.F., Mahowald, N.M., Merkel, U., Yu, H., Zuidema, P., Stuut, J.-B.W., 2020. Tropical rains controlling deposition of Saharan dust across the North Atlantic Ocean. Geophys. Res. Lett. 47, e2019GL086867.
van der Does, M., Pourmand, A., Sharifi, A., Stuut, J.-B.W., 2018. North African mineral dust across the tropical Atlantic Ocean: insights from dust particle size, radiogenic Sr-Nd-Hf isotopes and rare earth elements (REE). Aeolian Res. 33, 106–116.
Washington, R., Bouet, C., Cautenet, G., Mackenzie, E., Ashpole, I., Engelstaedter, S., Lizcano, G., Henderson, G.M., Schepanski, K., Tegen, I., 2009. Dust as a tipping element: the Bodélé depression, Chad. Proc. Natl. Acad. Sci. 106, 20564–20571.
Washington, R., Todd, M., Middleton, N.J., Goudie, A.S., 2003. Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations. Ann. Assoc. Am. Geogr. 93, 297–313.
Washington, R., Todd, M.C., Engelstaedter, S., Mbainayel, S., Mitchell, F., 2006a. Dust and the low-level circulation over the Bodélé depression, Chad: observations from BoDEx 2005. J. Geophys. Res. Atmos. 111.
Washington, R., Todd, M.C., Lizcano, G., Tegen, I., Flamant, C., Koren, I., Ginoux, P., Engelstaedter, S., Bristow, C.S., Zender, C.S., Goudie, A.S., Warren, A., Prospero, J. M., 2006b. Links between topography, wind, deflation, lakes and dust: the case of the Bodélé Depression, Chad. Geophys. Res. Lett. 33.
Weldeab, S., Lea, D.W., Schneider, R.R., Andersen, N., 2007. 155,000 Years of West African monsoon and ocean thermal evolution. Science 316, 1303–1307.
Yu, H., Tan, Q., Chin, M., Remer, L.A., Kahn, R.A., Bian, H., Kim, D., Zhang, Z., Yuan, T., Omar, A.H., Winker, D.M., Levy, R.C., Kalashnikova, O., Crepeau, L., Capelle, V., Chédin, A., 2019. Estimates of African dust deposition along the trans-atlantic transit

using the decadelong record of aerosol measurements from CALIOP, MODIS, MISR, and IASI. J. Geophys. Res. Atmos. 124, 7975–7996.
Zhao, W., Balsam, W., Williams, E., Long, X., Ji, J., 2018. Sr–Nd–Hf isotopic fingerprinting of transatlantic dust derived from North Africa. Earth Planet Sci. Lett. 486, 23–31.
Zhao, Y., Harrison, S.P., 2012. Mid-Holocene monsoons: a multi-model analysis of the inter-hemispheric differences in the responses to orbital forcing and ocean feedbacks. Clim. Dyn. 39, 1457–1487.