AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2013JD021283

Key Points:

- Holocene dust fluxes reconstructed from lake sediments at two sites in West Africa
- Low fluxes in early Holocene followed by rise from around 2 kyr B.P.
- Fluxes controlled by climate, sediment availability, and latterly human activity

Supporting Information:

- Readme
- Text S1
- Table S1

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Citation:
Cockerton, H. E., J. A. Holmes, F. A. Street-Perrott, and K. J. Ficken (2014), Holocene dust records from the West African Sahel and their implications for changes in climate and land surface conditions, *J. Geophys. Res. Atmos.*, *119*, 8684–8694,doi:10.1002/2013JD021283.

Received 3 DEC 2013
Accepted 24 JUN 2014
Accepted article online 26 JUN 2014
Published online 22 JUL 2014

Holocene dust records from the West African Sahel and their implications for changes in climate and land surface conditions

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Abstract We reconstructed aeolian dust accumulation during the Holocene from two radiocarbon-dated lake-sediment sequences from the Manga Grasslands in northeastern Nigeria in order to investigate long-term changes in the Harmattan dust system over West Africa and evaluate their possible causes. Flux values were low in the early Holocene, decreasing further to a minimum at around 6.2 kyr B.P. after which time they increased, steadily until around 2 kyr B.P. and then more sharply after this time. The long-term variations in dust flux agree broadly with changes in the exposed area of the Lake Chad Basin to the northeast of the study sites, which vary inversely with the volume of Paleolake Megachad. More proximal sources of dust, including the fine fraction of local dune sand and floodplains of nearby rivers, have also made a contribution to the total dust load during times of enhanced dune and fluvial activity. Sharp rises in dust flux over the past century may be related to human activity. Broad patterns of change in dust flux during the Holocene agree with other reconstructions over the same period. However, we see no evidence for a stepped rise during the middle Holocene, as seen at some sites from the northeastern tropical Atlantic, suggesting that controls on the Harmattan dust system have differed from those affecting dust deposition elsewhere across northern Africa.

1. Introduction

The northern and western parts of Africa form the largest source of aeolian dust in the world: between 300 and 700 Mt of dust are derived annually from the Sahara Desert alone [*Chiapello et al.*, 1997]. Globally, dust is an important component of the climate system. In the oceans, it plays an important role in fertilization and hence in carbon cycling [e.g., *Jickells et al.*, 2005]. In the atmosphere, dust particles have positive (through radiation absorption) and negative (through backscattering) radiative forcing effects [e.g., *Tegen*, 2003] and also act as cloud condensation nuclei [e.g., *Twohy et al.*, 2009]. On land, distal dust deposition makes an important contribution to soil parent material in some areas [e.g., *Muhs et al.*, 2010]. Dust fluxes vary on timescales from seasonal to millennial and longer in response to changes in effective moisture, wind speed, land surface cover, and anthropogenic activity [e.g., *Prospero and Lamb*, 2003; *Goudie and Middleton*, 2006]. On short (subannual to interannual) timescales, dust fluxes can be measured using instrumental methods, including remote sensing [e.g., *King et al.*, 1999] and surface dust collectors [e.g., *Stuut et al.*, 2005]. On longer (centennial to millennial and longer) timescales, fluxes have been reconstructed from dust preserved in ice cores and sediments [e.g., *Mahowald et al.*, 1999]. Here we report reconstructions of minerogenic dust flux during the Holocene over sub-Saharan West Africa based on the study of lake-sediment profiles from northeastern Nigeria. Today, this region falls under the influence of the prominent Harmattan dust plume, which is active during boreal winter. Our study addresses Holocene variations in Harmattan system and their possible causes.

At present, dust is derived from a number of well-defined regions in Africa, most notably the Bodélé Depression in Northern Chad (centered on ~16°N and 18°E), and several areas spread across Mali, Mauritania and southwestern Algeria [*Middleton and Goudie*, 2001] (Figure 1a), although recent studies have suggested that dust sources may be more widespread than previously thought, at least in the Sahara [*Crouvi et al.*, 2012]. Seasonal and geographical patterns of dust production and transport are complex, but previous workers have distinguished between a summer dust plume, which extends from east to west between ~17 and 20°N, and a winter plume, which lies further to the south (Figure 1a). During boreal summer, dust production is at a peak to the north of the West African monsoon front, where transport directed northeast to southwest over the

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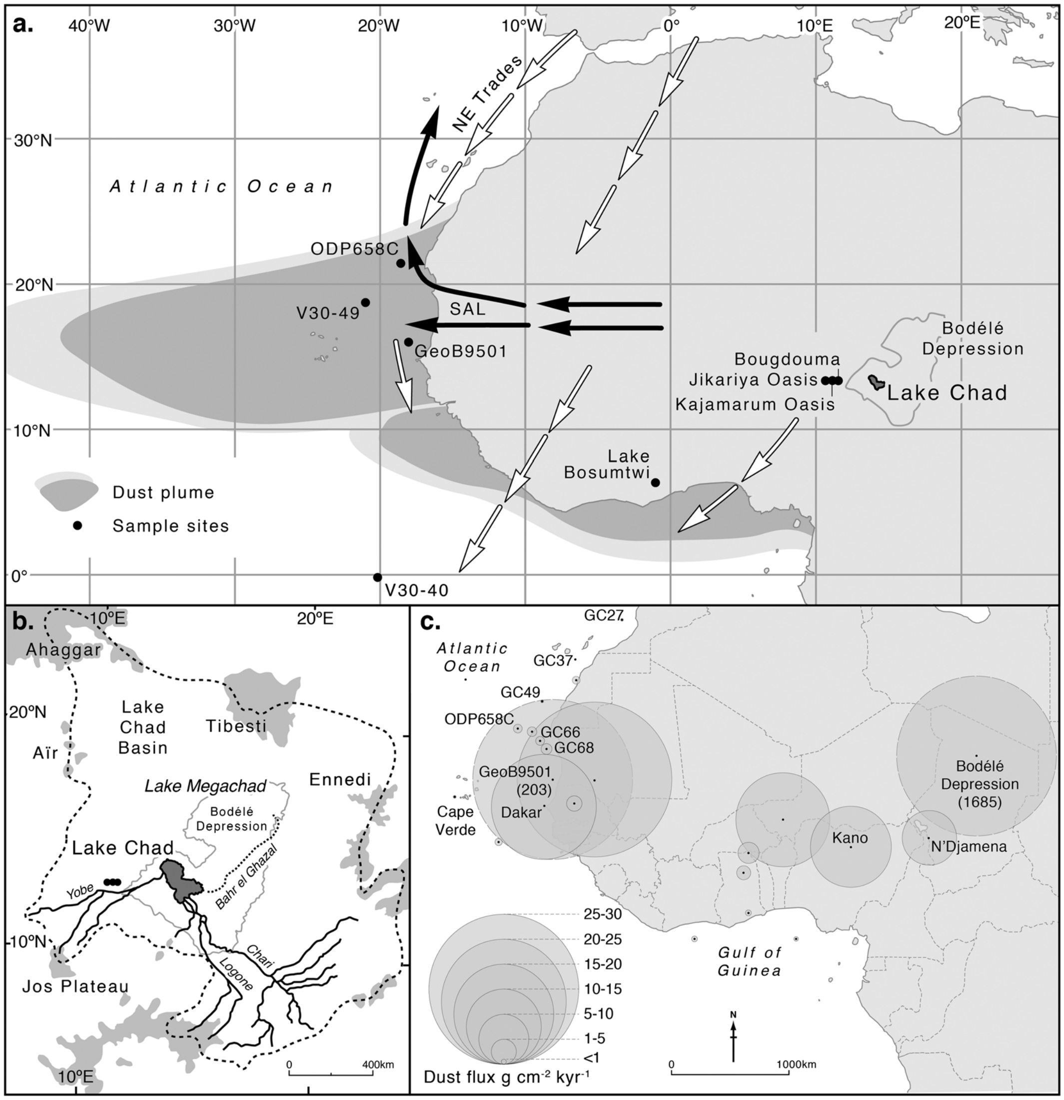

Figure 1. (a) Location of study sites and other localities referred to in the text. Dust plume extents over the ocean were determined from Total Ozone Mapping Spectrometer absorbing Aerosol Index data presented in *Engelstaedter and Washington* [2007]. Wind systems from *Zhao et al.* [2003]. SAL = Saharan Air Layer. (b) Map of Chad Basin, showing the main geographical features referred to in the text. (c) Modern and recent dust flux values across northern Africa from the Bodélé Depression [*Todd et al.*, 2007]; southern Chad (*Goudie and Middleton* [2001], from data in *Maley* [1982]); southwestern Niger [*Drees et al.*, 1993]; northern Nigeria [*McTainsh and Walker*, 1982]; Ghana [*Breuning-Madsen and Awadzi*, 2005]; coastal Senegal [*Orange and Gac*, 1990]; coastal Mauritania [*Gassani et al.*, 2005]; Gulf of Guinea [*Prospero*, 1996] northeastern tropical Atlantic close to the African coast [*Prospero*, 1996]; offshore from Cap Blanc and Cape Verde [*Ratmeyer et al.*, 1999]; ODP site 658C [*deMenocal et al.*, 2000]; GeoB9501 [*Mulitza et al.*, 2010] and CHEETA cruise (OCE437-7) core sites (prefixed by GC) [*McGee et al.*, 2013]. Estimated fluxes for the Bodélé Depression (1685 g cm^{-1} kyr^{-1}) and core site GeoB9501 (203 g cm^{-1} kyr^{-1}) are >>30 g cm^{-1} kyr^{-1} and not precisely depicted in the map.

northeastern tropical Atlantic is often associated with African easterly waves [*Engelstaedter and Washington*, 2007]. Fine dust particles are carried aloft and subsequently transported long distances over the Atlantic in the midtropospheric African easterly jet and Saharan air layer, although *Stuut et al.* [2005] argue that proximal dust deposition over the northeastern tropical Atlantic is mainly associated with low-level trade winds, even in summer, a view supported by *Skonieczny et al.* [2013]. During boreal winter, when the Intertropical Convergence Zone lies far to the south and rainfall over northern and western Africa is much reduced, the Bodélé Depression is an important source of dust to the West African Sahel, although the western Saharan sources remain active and there is significant transport of dust from both areas over the northeastern tropical Atlantic [*Engelstaedter and Washington*, 2007]. In summary, differentiation between winter and summer dust plumes is a difficult task and, off the coast of the northeastern tropical Atlantic especially, dust is supplied both in winter and summer and from a wide range of sources across northern Africa. Some authors therefore argue that dust flux records off the tropical Atlantic coast of West Africa cannot easily be linked to a specific wind system or source area [e.g., *Eglinton et al*., 2002; *Romero et al*., 2003].

The Lake Chad Basin is a major dust "hot spot" within northern Africa: remote sensing imagery and back trajectory modeling confirm that it supplies a significant quantity of dust to West Africa, including our study area, during the winter Harmattan season [e.g., *Sunnu et al*., 2013]. Paleogeographical changes in the basin have been a major control on dust export during the Holocene. The Bodélé Depression now occupies the northern basin of the huge Paleolake Megachad [e.g., *Grove and Warren*, 1968; *Servant*, 1973; *Kutzbach*, 1980], which had a maximum area of 361,000 km^2 during the Holocene [*Drake and Bristow*, 2006] and thus occupied a significant part of the Chad Basin in the past (Figure 1b). The Bodélé Depression was fed in part by runoff from the Tibesti Mountains and linked at various times during the Holocene to the southern Paleolake Megachad Basin by the Bahr-el-Ghazal channel. The former southern basin of Paleolake Megachad is occupied by the modern Lake Chad, fed mainly by the northward-flowing Chari River and its tributaries, which rise in the climatically-contrasting moist savanna zone of the Central African Republic and eastern Cameroon. Today, up to 10% of the Lake Chad inflow is derived from the Nigerian rivers, mainly the Yobe and Gana, which rise in the Jos Plateau to the southwest of the present lake (Figure 1b). The importance of the Bodélé Depression as a year-round focus of dust production arises from the large extent of erodible surface sediment (especially diatomite) [*Washington et al*., 2006], a lack of surface vegetation and local topographic control of low-level winds giving rise to the Bodélé low-level jet, which is especially active during boreal winter [*Washington and Todd*, 2005] and therefore leads to a peak in dust export during this season.

Modern and recent dust flux values across northern Africa and the adjacent tropical Atlantic vary strongly with location (Figure 1c), although methods of calculation vary so the quoted values may not be wholly comparable. Measures of dust export rates from the main dust production centers are scarce, although *Todd et al*. [2007] estimate dust emissions from the Bodélé Depression that equate to fluxes as high as 1685 ± 601 g cm^{-2} kyr^{-1}. Sediment accumulation data from southern Chad, southwestern Niger, northern Nigeria, and northern Ghana suggest a dramatic decline in dust flux downwind from source; values decline further southwestward over the Gulf of Guinea (Figure 1c). However, a model of declining flux with distance from source may be oversimple: in northern Ghana, for example, a significant proportion of Harmattan dust fall is of local origin [*Lyngsie et al*., 2011].

Particle-size characteristics of modern aeolian dust are also variable, with median diameters of up to ~70 μm in the southern Sahel [e.g., *McTainsh and Walker*, 1982], declining with distance from source to around 1 μm mean size over southern Ghana [*Afeti and Resch*, 2000]. Interestingly, dust exported from the Bodélé Depression itself is composed predominantly of very fine (1–2 μm) diatomite fragments, suggesting that Harmattan dust recovered downwind from the depression must contain admixtures of coarser-grained material derived from other, non-diatomite, sources within the Lake Chad Basin [*McTainsh and Walker*, 1982]. Compositionally, Saharan dust consists mainly of SiO_2 and Al_2O_3, with variable but lesser quantities of MgO, CaO, and Fe_2O_3 [*Goudie and Middleton*, 2006] as well as phytoliths, freshwater diatoms [*Pokras and Mix*, 1985], plant leaf waxes, and other organic matter [*Eglinton et al*., 2002].

Marine sediments are potential archives of long-term trends in dust flux. Several studies have reconstructed fluxes of terrestrially-derived material for the late Cenozoic [e.g., *Tiedemann et al*., 1994; *deMenocal et al*., 1993] and late Quaternary [*Pokras and Mix*, 1985]. Sediments from Ocean Drilling Program (ODP) site 658C, off Cap Blanc (Mauritania), GeoB9501, which lies to the south and approximately 20 km from the coast of Senegal, and the CHEETA (Changing Holocene Environments in the Eastern Equatorial Atlantic) sites, which lie on a transect between 19 and 31°N (Figure 1c), provide high-resolution records. ODP site 658C, which covers the past ~25 kyr, shows elevated terrigenous fluxes during the last glacial, the late-glacial stadial, and the late Holocene; and low values during the African Humid Period, which started with the late-glacial interstadial and extended into the middle Holocene, interrupted briefly by aridity during the Younger Dryas stadial [*deMenocal et al*., 2000; *Renssen et al*., 2003, 2006]. The sharp rise in dust in ODP core 658C at 5.5 kyr B.P. has been taken by some authors to indicate an abrupt widespread aridification over northern Africa during the middle Holocene [*deMenocal et al*., 2000]. The increase in continental diatom influx to the northeastern tropical Atlantic during the middle Holocene recorded in cores V30-49 (400 km southwest of Site 658C) and

V30-40 (located under the winter dust plume, 2000 km farther to the south) was broadly coincident with the middle Holocene rise in terrigenous flux at site 658C [*Pokras and Mix*, 1985]. The ^{230}Th-normalized flux calculations from the CHEETA sites that lie to the north and south of ODP site 658C provide evidence that is consistent with an abrupt increase in dust emission at the end of the African Humid Period, but with a somewhat later timing of 4.9 ± 0.2 kyr B.P. [*McGee et al.*, 2013]. The record from GeoB9501 is shorter, covering only the past 3500 years. Here a large increase in terrigenous flux after about 1700 Common Era was attributed to the onset of commercial farming in West Africa, whereas before that time, the changes in flux were in phase with indicators of continental effective moisture [*Mulitza et al.*, 2010].

Despite the existence of the ocean-core records, changes in dust flux over northern Africa during the Holocene remain poorly understood. Based on our knowledge of recent dust generation, it is likely that that the marine sediment archives of dust flux are composite records of both summer and winter transport of dust sourced from a wide area, although likely carried by the low-level trade wind and Harmattan system regardless of season. We present Holocene dust flux records from lake basins in the Manga Grasslands of NE Nigeria. These sites lie unequivocally in the path of the modern Harmattan (winter) dust plume [*McTainsh and Walker*, 1982; *Sunnu et al.*, 2013] (Figure 1a) and thus provide an excellent opportunity to investigate the evolution of this dust system during the Holocene. Using these records of dust flux along with published sequences from the northeastern tropical Atlantic, we address the following questions:

1. How has the flux of dust transported by the Harmattan system changed during the Holocene?
2. What are the similarities and differences between the records of dust flux recorded at different localities over northwest Africa and the adjacent ocean?
3. To what extent has the dust flux associated with the Harmattan system been controlled by climate (effective moisture, or precipitation minus evaporation, P − E), source-area changes (especially connected with the major water-level fluctuations of Paleolake Megachad), and human activity?
4. Have there been temporal variations in the relative importance of regional versus local dust sources in northeastern Nigeria?

2. Study Sites and Methods

We analyzed two well-dated lake-sediment sequences, from Jikariya Lake and Kajemarum Oasis, located in northeastern Nigeria. The sites lie in the Manga Grasslands (13°00′ to 13°30′N and 10°30′ to 12°00′E, 320–350 m a.s.l.), an area of numerous interdune depressions separated by stable barchanoid dunes covered by annual grasses and shrubs and occasional trees, located on the border between Nigeria and Niger in the West African Sahel (Figure 1a) [*Holmes et al.*, 1999]. The lake basins are surrounded by highly permeable dune sands and therefore do not receive fine sediment from surface runoff. The Manga Grassland sites are located ~800 km southwest of the Bodélé Depression and so are ideally located for the reconstruction of past aeolian dust export associated with the Harmattan system (see supporting information for details of sites, sediment sequences, methods, and chronologies). At the time of sediment recovery, Jikariya still hosted a shallow brine lake whereas the Kajemarum Oasis had been periodically dry since the major drought of the late 1960s to early 1970s [*Street-Perrott et al.*, 2000].

Aeolian mineral dust (<63 μm) was extracted from bulk sediment using a modified version of the procedure of *Rea and Janecek* [1982] (see supporting information for details). Dust fluxes (mass accumulation rates) were calculated from the product of dry bulk density, sedimentation rate, and measured dust content to allow direct comparisons with other sites [*Rea*, 1994]. At both sites, the dust records cover the past 10,000 years (all ages in this paper are in calendar years, unless otherwise stated). For Jikariya Lake, dust analysis was carried out at core intervals of between 1 and 10 cm (~20–200 years). Particle-size analysis was undertaken on dust extracts from this site using laser granulometry (further details in the supporting information). At Kajemarum Oasis, dust analysis was carried out every 2–10 cm (~30–200 years). No particle-size analysis was undertaken on dust extracts from this site.

3. Results

At Jikariya Lake dust flux values were low (0.4 and 5 g cm^{-2} kyr^{-1}, average = 2.8 ± 1.0 g cm^{-2} kyr^{-1}) during the early to middle Holocene, declining slightly between 10 kyr and 6.6 kyr B.P. (Figure 2a). After 6.6 kyr B.P., values rose steadily but unevenly, varying between 0.6 and 5 g cm^{-2} kyr^{-1} until 2 kyr B.P., with a transient

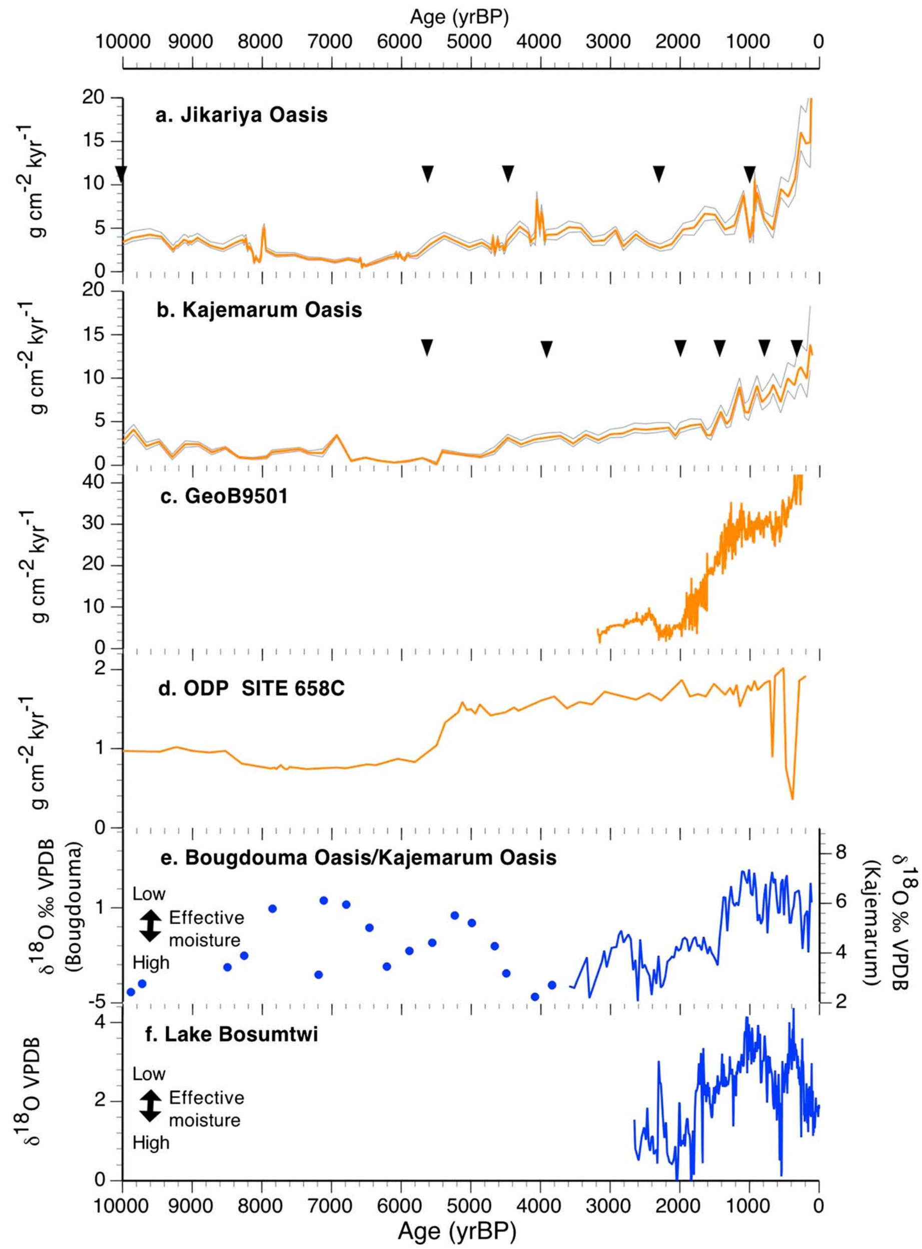

Figure 2. Variations in dust flux and effective moisture over West Africa during the Holocene. (a) Dust flux values from Jikariya Oasis: most recent 300 years not plotted. (b) Dust flux values from Kajemarum Oasis (determinations for the interval 5.5–0 kyr B.P. previously published in *Street-Perrott et al.* [2000]). Grey lines show 2σ uncertainties. Triangles denote dating points. Note that the long undated interval between ~10 and 6 kyr may render the flux values more uncertain than is indicated. (c) Dust flux values from GeoB9501 [*Mulitza et al.*, 2010]: most recent 300 years not plotted. (d) Dust flux values from ODP site 658C [*deMenocal et al.*, 2000]. (e) Carbonate oxygen-isotope values from the Manga Grasslands: Kajemarum Oasis (ostracod carbonate: solid line, 0–3.8 kyr B.P., right-hand scale: *Street-Perrott et al.* [2000]) and Bougdouma Oasis (fine-grained carbonate: filled circles, 3.8–10 kyr B.P., left-hand scale: *Téhet et al.* [1990]). Offsets between the values from the two sites reflect differences in basin hydrology and in the carbonate material analyzed, meaning that the values of the two data sets are not directly comparable. However, the data from Bougdouma extend the time series to the early part of the Holocene and attest to increased effective moisture during much of this interval. (f) Carbonate oxygen-isotope values from Lake Bosumtwi, Ghana [*Shanahan et al.*, 2009].

peak in flux to ~8 g cm^{-2} kyr^{-1} around 4 kyr B.P. Values increased further after 2 kyr B.P., and especially over the past 100 years, reaching a maximum of ~90 g cm^{-2} kyr^{-1} near the top of the sequence. At Kajemarum Oasis, early Holocene fluxes were between 0.4 and 5 g cm^{-2} kyr^{-1} (average = 1.9 ± 1.2 g cm^{-2} kyr^{-1}) and declined to minimum values at 5.5 kyr B.P. (0.2 g cm^{-2} kyr^{-1}). From the middle Holocene, dust fluxes increased gradually after 5.5 kyr B.P., followed by a rapid rise commencing 1.6 kyr B.P. and reaching a maximum of 13 g cm^{-2} kyr^{-1} close to the top of the sequence, around 100 years ago (Figure 2b). In evaluating the measured flux values, we have to consider that the preparation method used here necessarily removes several components known to be present in modern Harmattan dust, namely biogenic silica, organic matter, and carbonate (see supporting information). The calculated fluxes should therefore be regarded as minimum values.

4. Discussion

4.1. Patterns of Dust Flux in the Manga Grasslands

The broad similarity between the two dust flux records suggests that they were not controlled purely by dust production within the individual local basins. Moreover, the low-silt content of the local sand dunes, coupled with the small proportion (<3%) of the land area in the Manga Grasslands that consists of fine-grained soils and sediments [*Mortimore*, 1989], supports the view that the individual lake catchments would not have been significant silt sources. Other local, but less proximal, aeolian sediment sources around the periphery of the Manga Grasslands include fluviodeltaic deposits of the Yobe and Gana Rivers immediately to the south and east [*Thiemeyer*, 1998; *Gumnior and Thiemeyer*, 2003; *Gumnior and Preusser*, 2007] as well as the Bama Ridge, which is a high shoreline of Paleolake Megachad [*Thiemeyer*, 1992] to the southeast, and linear dune fields that lie to the south [*Gumnior and Thiemeyer*, 2003; *Stokes and Horrocks*, 1998]. All of these contain a significant silt fraction of up to about 10% [e.g., *Gumnior and Preusser*, 2007] and so are potential dust sources.

For Jikariya Lake, we use median grain size as a proxy for transport distance and hence provenance [*Pye*, 1987; *McTainsh et al*., 1997; *Donghuai*, 2004; *Evans et al*., 2004; *Prins et al*., 2007]. Fine particles (<20 μm) are thought to indicate far-traveled dust (especially from the Bodélé Depression), and coarser grains (20–63 μm) are thought to originate from the more proximal sources listed above.

Median grain size ranged from 12 to 54 μm at Jikariya Lake during the Holocene (Figure 3e). In the early to middle Holocene, median grain size was larger (20 to 54 μm), declining (to between 12 and 34 μm) in the later Holocene. The shift in grain size, from coarser particles and highly fluctuating median values in the early Holocene to finer particles and less variable median values from the middle Holocene onward, corresponds to the middle Holocene increase in dust flux (Figure 2a). At most levels within the Jikariya core, median grain size falls within the 20 to 40 μm range, which is broadly consistent with the grain size of dust deposited over northeast Nigeria today [*McTainsh and Walker*, 1982]. A large portion of this dust was therefore probably derived from the greater Chad Basin and transported by the Harmattan system, although some (on average, about 30%, based on the proportion of material >40 μm) originated from more local sources on the periphery of the Manga Grasslands, as outlined above.

During much of the early to middle Holocene, the potential of the Lake Chad basin to supply dust would have been limited, owing to the existence of a much larger lake than today. The Holocene lake-level history of Paleolake Megachad, therefore, provides a record of the times when the basin was a major dust source (Figure 3a). From the early to middle Holocene up until about 4.5 kyr B.P., the basin was occupied by a greatly expanded lake for much of the time, with its level at 329 ± 1.8 m a.s.l. and an area of 361,000 ± 13,000 km^2 [*Thiemeyer*, 1992; *Schuster et al*., 2005; *Drake and Bristow*, 2006]. During this highstand, the extent of the erodible surface for wind deflation would have been restricted. Abrupt, millennial-scale falls in water level occurred around 8.3 kyr B.P. and possibly at other times [*Servant*, 1973; *Servant and Servant-Vildary*, 1980; C. Bristow, personal communication, 2014]; during these intervals there would have been short-lived increases in the dust-source area. However, apart from the lake-level fall around 8.3 kyr B.P., these regressions are poorly constrained. An abrupt fall in lake level after ~4.5 kyr B.P., possibly leading to complete desiccation, was followed by a lesser highstand at 3.4 kyr B.P., with lake level at 289 ± 1.4 m and a water-covered area of 141,000 ± 7,000 km^2 [*Drake and Bristow*, 2006]. There were further falls in water level between around 1.8 and 1 kyr B.P. [*Servant*, 1973; C. Bristow, personal communication, 2014] with surface water finally disappearing from the Bodelé Depression around the latter date. In summary, stepped falls in lake level were accompanied by

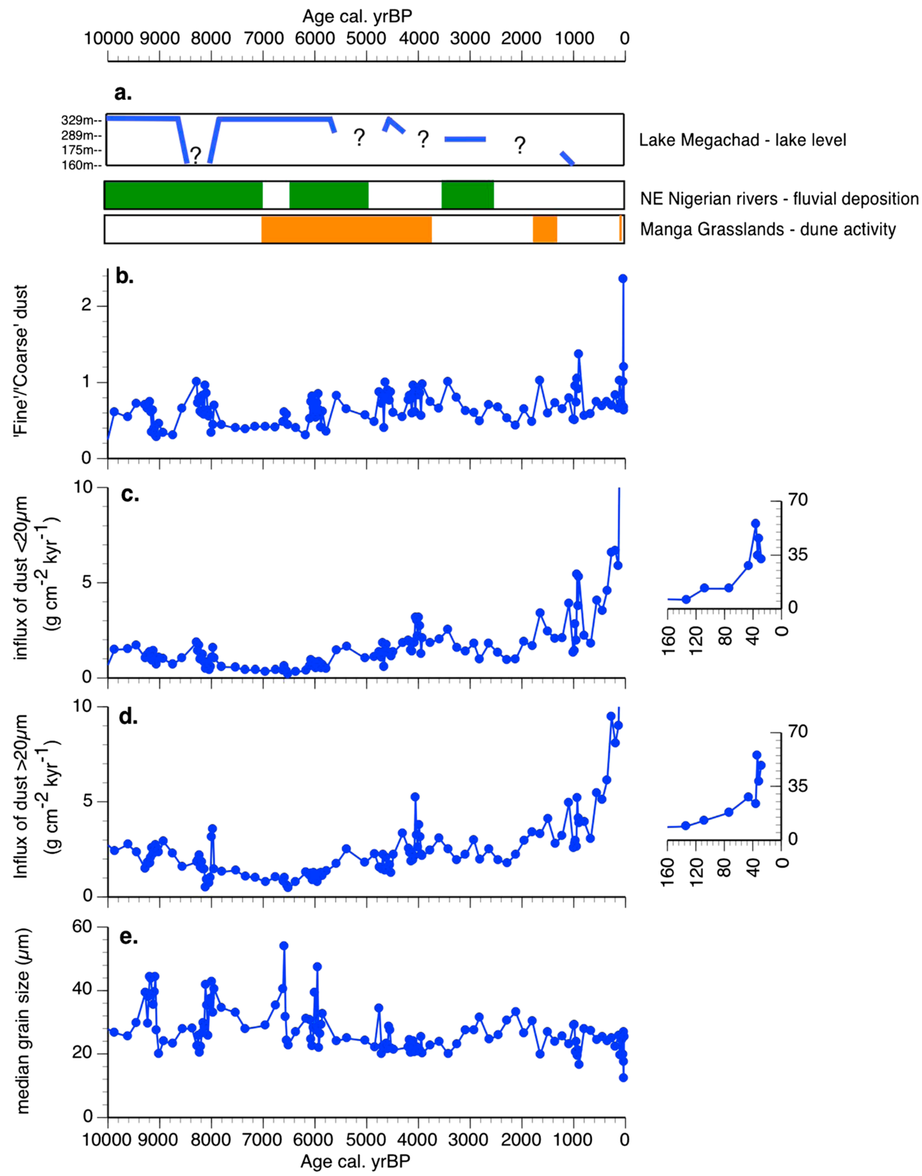

Figure 3. Grain size characteristics of the aeolian dust component of sediments from Jikariya Oasis during the Holocene, together with changes in regional paleogeography. (a) Phases of fluvial deposition by river systems of NE Nigeria [*Gumnior and Preusser*, 2007], dune emplacement in the Manga Grasslands [*Holmes et al.*, 1999], and highstands of Lake Chad are also shown. For the Paleolake Megachad record, approximate timings of the highstands at 329 m a.s.l. (the Bama Ridge), 289 m a.s.l., and 175 m a.s.l. are shown. The 160 m a.s.l. level represents intervals when the Bodélé Depression was dry. See text for further details and references. (b) The ratio of "fine" to "coarse" dust: for definitions, refer to supporting information. (c) Influx of dust <20 μm. (d) Influx of dust >20 μm. (e) Median grain size. Small graphs in Figures 3b and 3c detail changes in dust flux fractions over the past 160 years: units are the same as on the main graphs.

dramatic increases in the erodible surface area, around 4.5 and between 1.8 and 1 kyr B.P., with the possibility of abrupt, millennial-scale regression events around 8.3 kyr B.P. and perhaps at other times during the early Holocene.

Although the lake-level history of Paleolake Megachad provides a good proxy for the changing area of dust source during the Holocene, it is poorly representative of the hydrological changes affecting the Manga Grasslands because Lake Chad has a vast catchment. At present, most of the inflow is derived from the Sudano-Guinean zone to the south of the lake although during the more humid intervals of the early and middle Holocene, inputs from the present-day Sahara and Sahel would also have been important [*Gasse*, 2002]. Therefore, in order to investigate the local climatic controls on dust flux, we examine effective moisture changes

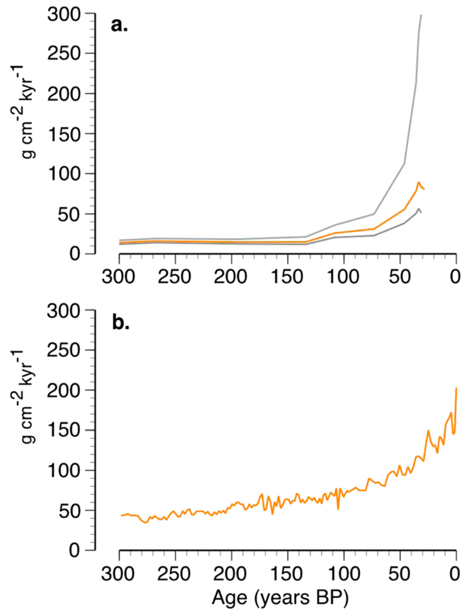

Figure 4. Changes in dust flux over the past 300 years from (a) Jikariya Oasis (this study: grey lines show 2σ uncertainties) and (b) GeoB9501 [*Mulitza et al.*, 2010].

in the Manga Grasslands using carbonate oxygen-isotope records from two sites, namely Kajemarum Oasis for the past ~4 kyr and Bougdouma Oasis, which lies ~65 km to the east, for the middle and early part of the Holocene [e.g., *Street-Perrott et al.*, 2000; *Téhet et al.*, 1990] (Figure 2e). Such records provide a proxy for the levels of effective moisture in the Manga Grasslands and immediate surroundings. During drier intervals, such areas, termed here "local," may also have been sources of dust. We note also the broad-scale similarity between the Manga Grasslands oxygen-isotope records and the δ^{18}O history of Lake Bosumtwi (Ghana) for the past 2.8 kyr B.P. [*Shanahan et al.*, 2009] (Figure 2f), suggesting coherence in late Holocene effective moisture changes over West Africa associated with the summer monsoon.

From 10 to 7.2 kyr B.P., the Manga Grasslands experienced elevated P − E, at a time when a large area of the Paleolake Megachad Basin was occupied by a lake, as discussed above. Elevated P − E in the Manga indicated by predominantly low oxygen-isotope values at Bougdouma is consistent with pollen records showing Sudanian savanna vegetation and a largely stable, vegetated land surface at that time [*Salzmann and Waller*, 1998; *Waller et al.*, 2007]. The transient fall in the water level of Lake Chad around 8.3 kyr B.P., coupled with evidence of reduced effective moisture in the Manga Grasslands, is associated with short-term increases in dust flux in Jikariya (the resolution of the Kajemarum record is apparently too low to record this) suggesting that a brief increase in the area of the Lake Chad Basin dust source, and/or a reduction in local effective moisture and hence a greater local dust source, led to an increase in dust flux.

Prior to about 6 kyr B.P., the slightly larger median grain size, which suggests the supply of a greater proportion of locally-derived dust, is puzzling, given the elevated effective moisture for much of this early Holocene interval. Enhanced dune activity in the Manga Grasslands [*Stokes and Horrocks*, 1998] and the presence of thin lenses of fine dune sand in the early Holocene lake sediments from Jikariya and Kajemarum provide further evidence of local aeolian activity during this moist interval. Although dust (as opposed to sand) sources do not appear to have been very active for much of this time, the dust that was being produced was largely of local origin and may have been derived from the fine fraction of local dunes and especially the floodplains of the river systems to the south of the Manga Grasslands. The fact that the river systems were active at this time [e.g., *Gumnior and Preusser*, 2007] (Figure 3a) suggests that the influx of aeolian sand and dust to the closed basins of the Manga Grasslands may have been caused by increased sediment supply, especially during the dry season when river flow would have been reduced, possibly coupled with increased windiness [e.g., *Drake and Bristow*, 2006] in an otherwise well-vegetated landscape [e.g., *Waller et al.*, 2007].

A small but steady rise in dust flux at both sites in the Manga Grasslands commenced sometime after 6 kyr B.P. At approximately the same time, rising δ^{18}O values at Bougdouma Oasis [*Gasse*, 2002] suggest decreasing effective moisture over the Manga Grasslands. Moreover, a reduction in median grain size at this time suggests a shift to a greater relative importance of more distant dust sources. A transient increase in dust around 4 kyr B.P. in Jikariya (the sampling resolution at Kajemarum was insufficient to resolve this event) may be associated with a drying event in the Manga Grasslands as well as the increase in dust-source area in the Chad Basin, as indicated by the evidence of lake regression from the Bahr-el-Ghazal between 4.5 and 3.8 kyr B.P. [*Drake and Bristow*, 2006].

The most significant event in the dust records, however, is the major increase in dust flux starting around 1.6 kyr B.P., which coincided with the reduction of effective moisture in northeast Nigeria and possibly with the final desiccation of the Bodélé Depression, which was completed around 1 kyr B.P. [C. Bristow, personal communication, 2014]. After this time, dust fluxes in both basins remained high but were variable. A further dramatic increase in dust flux starting about 100 years ago is seen in the Jikariya record (Figure 4a), although the uncertainties in the calculated flux values increase dramatically toward the top of the sequence. This recent increase is not present in the Kajemarum record, however, because the sequence is truncated by recent erosion [*Street-Perrott et al*., 2000]. It is possible that this very recent increase represents the rise of commercial agriculture across the West African Sahel, as has been noted elsewhere [*Mulitza et al*., 2010] (Figure 4a). The fining of median grain size in this period suggests that far-traveled dust made a significant contribution to this increase (Figure 3b).

4.2. Comparison With Dust Flux Records From the Northeastern Tropical Atlantic

The dust flux histories from the Manga Grasslands show some similarities to, and some marked differences from, other West African dust records. The broad pattern of slightly elevated flux values for the early Holocene, minimum values in the middle Holocene, and higher values in the late Holocene is present in the Manga Grassland records and the marine sediments records from the northeastern tropical Atlantic [*deMenocal et al*., 2000; *McGee et al*., 2013]. However, the timing of the increase in dust flux after the middle Holocene differs. In the marine sequences, a sharp rise in dust occurred between about 5.5 and 4.9 kyr B.P., whereas in the Manga Grasslands, the increase in dust flux after the middle Holocene was initially gradual but becoming more rapid after about 1.6 kyr B.P. These observations therefore point to significant spatial differences in the nature and timing of dust deposition over West Africa during the late Holocene. However, as discussed above, observations indicate that the same wind system, i.e., the low-level Harmattan—NE Trade wind system—is mainly responsible for dust deposition both over northeastern Nigeria and the northeastern tropical Atlantic, at least at present. Spatial differences in dust fluxes during the late Holocene may therefore be better explained by changes in the availability of a dust source, rather than major differences in the behavior of the wind systems affecting the two contrasting regions. The Lake Megachad Basin and Bodélé Depression, which is major dust source for the Manga Grasslands, appear to provide little dust to the northeastern tropical Atlantic, which is instead supplied mainly by a large area further to the north and west, in the present-day Sahara and northern Sahel [*Skonieczny et al*., 2013]. Significantly, there is lake level and paleovegetation evidence to suggest a sharp fall in effective moisture in these areas during the middle Holocene, between about 6.7 and 5.5 kyr B.P. [*Hoelzmann et al*., 2004], which could explain the rise in dust export over the tropical North Atlantic at this time. In contrast, the Lake Megachad Basin still contained a large volume of water for much of the middle Holocene and only became a significant source of dust as the water level in the Bodélé Depression fell dramatically, sometime after about 1.8 kyr B.P. Smaller-scale changes in wind regime may still have played some role in controlling dust regimes, however. In particular, *Kröpelin et al*. [2008] suggested that the late Holocene rise in magnetic susceptibility in the sediments of Lake Yoa, which lies upwind of the Bodélé Depression, indicate that the modern wind regime had become established by about 2.7 kyr B.P., which is consistent with the onset of dust increase in the Manga Grasslands records. Broad similarities between the records from the Manga Grasslands and marine core GeoB9501 suggest some degree of coherence in the behavior of the two dust-transporting systems, especially since about 1.5 kyr B.P. The lack of similarity between GeoB9501 and ODP site 658C, both in terms of the changes in flux and the absolute flux values, remains puzzling although the high values at the former site have been attributed to its proximity to the West African coast and to adjacent dust-producing areas in present-day Mauritania [*Mulitza et al*., 2010]: moreover, contrasting methods were used to calculate dust fluxes in the respective studies.

5. Conclusions

Results from the two lake sites studied here show that aeolian dust flux was low and declining over the Manga Grasslands during the early Holocene, reaching a minimum value in the middle Holocene around 6 kyr B.P. and then rising gradually until around 1.6 kyr B.P., after which it increased rapidly. Variations in the Harmattan dust system over northeastern Nigeria appear to have been controlled by changes in the exposed area of the main regional dust source, which is likely to have been the bed of Paleolake Megachad, especially the Bodélé Depression. More localized dust sources overprinted this broad pattern of change; a decline in median grain size in the middle Holocene suggests that proximal sources may have contributed a decreasing relative proportion of dust to the Manga Grasslands as the Megachad Basin became relatively more important as a dust source in the latter part of the Holocene. We see no evidence for an abrupt increase in dust flux around 5.5 kyr B.P. as seen in ODP site 658C, suggesting that the latter was not broadly representative of Sahelian and Saharan aridity during the Holocene, contrary to what has previously been suggested [*deMenocal et al*., 2000]. This may indicate differing behavior of the source regions. However, low fluxes in the early Holocene and higher fluxes in the later Holocene characterized both wind systems. A further rise in dust flux at one of our sites, Jikariya Oasis, over the past century may attest to a recent anthropogenic increase in dust, as seen elsewhere in West Africa: efforts to reduce the uncertainties in flux estimates for Jikariya Oasis for the past ~100 years would help to confirm this.

Acknowledgments
This work was funded by the UK NERC (grant GST/02/631 to F.A.S-P., studentship to H.C., and radiocarbon dating allocation 562/1293 and 682/1296). We thank C. Bristow, M. Waller, D. Mauquoy, and M. Blaauw for invaluable discussion and two anonymous referees for constructive comments.

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