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Title: West African Monsoon dynamics inferred from abrupt fluctuations of Lake Mega-Chad.

Short title: Lake Mega-Chad fluctuation since the Last Glacial Maximum

Simon J. Armitage[a], Charlie S. Bristow[b], and Nick A. Drake[c]

[a]Centre for Quaternary Research, Department of Geography, Royal Holloway University of London, Egham, Surrey, TW20 0EX, United Kingdom.
[b]Department of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London, WC1E 7HX, United Kingdom.
[c]Department of Geography, King's College London, Strand, London, WC2R 2LS, United Kingdom.

Corresponding author: Simon J. Armitage
E-mail: simon.armitage@rhul.ac.uk Tel +44 (0)1784 276124

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Abstract
From the deglacial period to the mid-Holocene, North Africa was characterised by much wetter conditions than today. The broad timing of this period, termed the African Humid Period, is well known. However, the rapidity of the onset and termination of the African Humid Period are contested, with strong evidence for both abrupt and gradual change. We use optically stimulated luminescence dating of dunes, shorelines and fluvio-lacustrine deposits to reconstruct the fluctuations of Lake Mega-Chad, which was the largest pluvial lake in Africa. Humid conditions first occur at ~15 ka, and by 11.5 ka Lake Mega-Chad had reached a highstand, which persisted until 5.0 ka. Lake levels fell rapidly at ~5 ka, indicating abrupt aridification across the entire Lake Mega-Chad Basin. This record provides strong terrestrial evidence that the African Humid Period ended abruptly, supporting the hypothesis that the African monsoon responds to insolation forcing in a markedly non-linear manner. In addition, Lake Mega-Chad exerts strong control on global biogeochemical cycles since the northern (Bodélé) basin is currently the World's greatest single dust source, and possibly an important source of limiting nutrients for both the Amazon basin and equatorial Atlantic. However, we demonstrate that the final desiccation of the Bodélé Basin occurred around 1 ka. Consequently, the present-day mode and scale of dust production from the Bodélé Basin cannot have occurred prior to 1 ka, suggesting that its role in fertilizing marine and terrestrial ecosystems is either overstated or geologically recent.

Significance statement
15,000-5,000 years ago, North Africa was wetter than today, with wetlands and lakes formed in the Sahara due to an enhanced monsoon. We reconstruct the lake level history of Lake Mega-Chad, when it was the largest African lake, and demonstrate that this humid period ended abruptly 5,000 years ago, indicating that the African monsoon exhibits a non-linear response to insolation forcing. The northern basin of Lake Mega-Chad, currently the World's greatest dust source, became dry around 1,000 years ago. Prior to that time dust output from the northern basin would have been limited, and suggestions that this dust plays an important role in fertilizing Atlantic and Amazonian ecosystems are either overstated or only true for the last thousand years.

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1. Introduction
The West African Monsoon (WAM) is key to our understanding of the African climate system and the impacts of future climate change upon its population. Climatically, the WAM is a major component of the global monsoon belt which regulates moisture availability in the low latitudes, and is sensitive to climate dynamics in both the high latitudes and the tropics. From a human perspective, the WAM represents the dominant control upon agricultural productivity in a densely populated region which is heavily reliant on subsistence agriculture (1). The broad pattern of WAM dynamics since the Last Glacial Maximum (LGM) are well known, with initially arid conditions being replaced by a more humid phase, sometimes termed the African Humid Period (AHP), which lasted from the deglacial period to the mid-Holocene. However, palaeoclimate proxy data from North Africa and adjacent areas of the Atlantic provide contrasting evidence for the rate and timing of these changes, leading to uncertainty over the controls upon WAM dynamics.

2. West African Monsoon dynamics
The widely cited terrigenous dust record from Ocean Drilling Program (ODP) site 658C indicates abrupt onset and termination of the AHP at 14.8 and 5.5 ka respectively (2). In contrast records from Lake Yoa within the Sahara (3-5), and the Gulf of Guinea (1), are interpreted to indicate gradual aridification over the past 6 ka, with pollen data suggesting the onset of full desert conditions at 2.7 ka. Reviews of lake level change within the southern Sahara and Sahel indicate additional millennial to centennial changes

superimposed on the broad pattern of increase and subsequent decrease in humidity since the LGM (6). These three scenarios, (a) abrupt onset and termination, (b) gradual change, and (c) a broad trend with shorter term variability, are supported to a greater or lesser extent by climate models in which an enhanced WAM is linked to summer-season insolation in the northern hemisphere, which peaked around 10 ka and then gradually declined (7-9). Abrupt changes in North African climate can be simulated by biogeophysical feedbacks (7) while a gradual change in rainfall is simulated by a coupled transient simulation model (9), where vegetation feedbacks are muted and more localised. Alternatively, a "flickering switch" may be simulated, in which the climate system and ecosystems in north Africa have two stable configurations, a green state and a desert state, with strong centennial scale fluctuations across the transition due to non-linear biogeophysical feedback (10). In addition, many studies attribute arid-humid (humid-arid) transitions at individual sites to the northward (southward) migration of the inter-tropical convergence zone (ITCZ) in response to precessionally driven increases (decreases) in summer season insolation amounts in the northern low-latitudes. However, several recent studies have indicated that at least some arid phases observed in the African palaeoclimate record are due to in-situ weakening of rainfall associated with the ITCZ (11-13), or contraction of this rainfall band in an interhemispherically symmetric manner (14). While existing proxy and climate model data yield important insights into the drivers and mechanisms governing WAM strength, the paucity of regional scale terrestrial records inhibit the evaluation of competing theories (15).

We present a regional scale record of north-central African moisture balance, derived by optically stimulated luminescence (OSL) dating sedimentary deposits associated with the rise and fall of Lake Chad and its earlier incarnation, Palaeolake Mega-Chad. The latter was the largest freshwater lake in Africa, and probably the largest pluvial lake on Earth. During the early-mid Holocene wet phase, Lake Mega-Chad attained an area of 361,000 km^2 (16-18) and a depth of up to 160 m (Figure 1). Palaeolake Mega-Chad has the potential to provide an important record of WAM dynamics since it is: (a) Sensitive to changing moisture balance due to its shallow depth and large surface area; (b) Dominated by fluvial inputs, unlike smaller North African lakes where groundwater can dominate and (c) Located in central north Africa, thereby integrating moisture from tropical and desert latitudes (Figure 1a and b). In addition, Lake Chad potentially acts as a climate driver in itself, projecting tropical moisture c.1,000 km northwards during humid periods, thereby providing an efficient moisture source in the absence of long range atmospheric moisture delivery (19), and allowing dust production in the Bodélé depression during arid periods (20, 21). This dust production may further enhance aridity by supressing rainfall (22). This dual role as alternate moisture and dust source is made possible by the geography of the Palaeolake Mega-Chad catchment, which feeds two interlinked basins (Figure 1c). The southern (Chad) basin contains present day Lake Chad, and is fed primarily by the tropical catchments of the Chari River. The northern (Bodélé) basin is presently hyper-arid and is fed either by Saharan catchments, or by overflow from the Chad Basin via the Bahr el Ghazal (BEG) sill at an elevation of 287 m (Figure 1c). The BEG sill is the lowest point in the watershed between the Chad and Bodélé basins. A single lake (Mega-Chad) is formed when lake levels exceed this elevation, and fluctuations observed in one basin are common to both. Conversely, ages for samples below 287 m only constrain lake levels in the basin where they were collected, except that the lakes in both basins must be below the elevation of the BEG sill at that time. Both basins contain (formerly) submerged aeolian dunes, extensive relict shorelines and fluvio-lacustrine sediments indicative of past lake fluctuations. We used OSL and radiocarbon dating of these deposits, combined with existing records from the basin, to document the fluctuations of Lake Chad and construct a regional scale record of WAM variability.

3. Fluctuations of Palaeolake Mega-Chad

A reconstruction of Lake Mega-Chad levels, based upon new and published OSL and radiocarbon ages (sample details are provided in Table S1), is presented in Figure 2. Sustained aridity in the period immediately after the LGM is evident in both basins. Transverse dunes are preserved in the Chad basin between 19 and 16 ka (NG33-36) while barchan dunes preserved under freshwater diatomite in the Bodélé date from 17 to 15 ka (CH16, 22 and 51). The transverse dunes on the bed of Lake Chad are indicative of drier than present-day conditions in the Chari catchment prior to ~16 ka. A single age of 19 ± 2 ka (NG41) for fluvial sands at Dalori Quarters in the Chad Basin, suggests elevated lake levels at that time. There are no analytical reasons for doubting the accuracy of this age. However, runoff from the Niger-Benue and Sanaga rivers was negligible between 24 and 17 ka (1), and a transverse dune on the bed of Lake Chad yielded ages of 19.0 ± 2.3 and 18.7 ± 2.2 ka (NG35 and NG35), leading us to conclude that the age for NG41 is incorrect. Cessation of dune migration at approximately 15 ka (CH16, 22, both 15.0 ± 1.8 ka) is taken to indicate increased humidity in the Lake Mega-Chad catchment at this time, and a radiocarbon age on a mollusc from Monguno confirms a lake level around 10 m above present day by 13.7-13.4 cal. ka BP (SUERC-18367). A cluster of ages for alluvial sedimentation on the Komadugu palaeofloodplain from 12.9 to 11.5 ka (23) is suggestive of rapidly rising lake level. A suite of ages for beach ridges in both the Chad and Bodélé Basins, and fluvial valley fills in the Chad Basin, indicate that lake high stands were reached during the early and mid-Holocene. The altitude of most of these ages cluster around the prominent 329 m shoreline found throughout the basin (16). This level is largely determined by the Mayo Kebbi overflow at 325 m, which leads to the Gulf of Guinea via the Benue and Niger Rivers. Two samples (CH46 and CH73) are found below this level, indicating that lake outflow was not constant throughout periods of high lake levels. The ages for Lake Mega-Chad beach ridges cluster at 11.5-10.4 ka (CH74, NG6, 7), 9.4-8.1 ka (NG8, 11, 12, 40) and 6.6-5.4 ka (CH44, 46, 73 and NG9, 10, 38, 39). Although the uncertainty terms associated with individual OSL ages preclude the unambiguous attribution of these deposits to separate lake highstands, the geomorphic setting of the sample sites (SI Section 4.5), and existing North African lake-level chronologies (6) suggest that this is the case.

Three published (17) radiocarbon ages (4.52-4.16, 5.31-4.98 and 5.44-4.97 cal. ka BP) for shells from a regressive shoreline (325-330 m) at Goz Kerki extend the mid-Holocene highstand to ~5 ka, after which the lake level fell dramatically and dunes of the Erg du Djourab within the northern Bodélé catchment became active. Reactivation of these transverse dunes, which occur between elevations of ~225 and 300 m, date to between 4.7 and 3.1 ka (24). Dune samples at ~225 and ~265 m yield ages of 4.7 ± 0.2 and 4.7 ± 0.3 ka, suggesting that lake level rapidly fell ~100 m immediately prior to this time (24). The uncertainties on the 4.52-4.16 cal. ka BP age for highstand deposits (17), and the 4.7 ± 0.2 and 4.7 ± 0.3 ages for lower lying dunes are consistent with a lake-level fall at ~4.5 ka. However, this explanation requires an extremely rapid desiccation at ~4.5 ka, and the 4.52-4.16 cal. ka BP age from Goz Kerki is itself inconsistent with the two other ages presented (17) for the same regressive shoreline (5.31-4.98 and 5.44-4.97 cal. ka BP). Consequently, the most parsimonious conclusion is that lake-levels fell at ~5 ka, and that the 4.52-4.16 cal. ka BP age may be erroneous. For most of the period 4.7-3.1 ka, the level of Lake Chad was beneath the BEG sill, precluding the transfer of tropical moisture into the Bodélé depression via surface drainage. Human occupation of the abandoned bed of Lake Mega-Chad near the margins of present-day Lake Chad dates from 3.8 ka onwards, and indicates the permanence of its demise (25, 26).

By ~3 ka the Erg du Djourab dunes were stabilised and water levels rose to 295 m in Lake Chad, forming the Ngelewa ridge (NG29, 31, 32). These OSL ages are in good agreement with a 3,200 cal. years BP radiocarbon age for the same event (27). This lake level is consistent with the height of the BEG sill, and would have allowed flow from Lake Chad into the Bodélé basin, forming a lake. After 3 ka, lake levels fell again, though sands interpreted as a small delta at the northern end of the BEG at 185 m elevation (CH62, 2.4 ± 0.1 ka) indicate surface flow into the Bodélé basin from Lake Chad at this time. Final desiccation of the Bodélé occurred after 1.06-0.93 cal. ka BP, the radiocarbon age (SUERC-18366) for an in-situ articulated freshwater bivalve buried in the diatomite at the base of the basin. Although the level of Lake Chad fell beneath the level of the BEG sill, it never became completely dry. Over the past thousand years Chad has repeatedly oscillated between the present level (c.280 m) and 286 m (28).

4. Comparison with other African Monsoon records.

4.1. The last deglacial period

The presence of active sand dunes indicating drier than present conditions in the Chad Basin between 19 and 16 ka, and in the Bodélé basin between 17 and 15 ka, is consistent with most records of North African palaeoclimate (12, 29). Between 24 and 17 ka, sea surface salinity (SSS) in the Gulf of Guinea is consistent with open ocean values, indicating negligible freshwater runoff from the Niger-Benue and Sanaga rivers (1). Neodymium (Nd) isotope records from the Gulf of Guinea sediments indicate a progressive northwards movement of the summer WAM rainfall front from 19.4 ka onwards (30). By 14.6 ka, the front had entered the Sanaga basin at ~7°N, above which latitude the WAM delivers moisture to the southern portions of the Chad catchment. The Gulf of Guinea SSS record (1) implies increased runoff from the Niger-Benue and Sanaga rivers from 14.5 ka, while at Lake Bosumtwi, Ghana, lake levels had risen above the present elevation by 14.5 ± 0.6 ka and rose again after ~14.3 ka (31). These data support our inference that the cessation of dune activity in the Mega-Chad basin at ~15 ka represents a geomorphic response to increased humidity.

Weldeab et al., (1) infer increased runoff from 14.5 ka, followed by aridity around 12.9-11.5 ka, a pattern which is consistent with Atlantic dust flux record (2) and lake fluctuations and sedimentation rate in Lake Bosumtwi, Ghana (13, 31). In this context, it is difficult to interpret the 12.9-11.5 ka cluster of ages for Komadugu floodplain sediments (23) as representing lake-full conditions, though clearly some moisture was present in this portion of the Lake Mega-Chad catchment. During the 12.9-11.5 ka arid phase a marked decrease in runoff is observed, though the Nd composition of Gulf of Guinea sediments does not change (30), implying an in-situ weakening of ITCZ rainfall rather than southward migration of the ITCZ itself.

4.2. 11.5 to 5.0 ka

The period 11.5 to 5.5 ka constitutes the main humid phase within the African Humid Period (2). In the Gulf of Guinea, the end of the 12.9-11.5 ka arid phase is marked by the largest and most abrupt decrease in SSS during the last 155,000 years, indicative of a pronounced increase in riverine runoff (1). Similarly, lake-levels along an east-west transect from Ethiopia to Ghana display a rapid and broadly synchronous rise (6), and our data from both the Chad and Bodélé basins indicate a lake highstand at this time.

Between 11.5 and 5.0 ka, ages for lake highstand sediments cluster at 11.5-10.4, 9.4-8.1 and 6.6-5.0 ka, possibly indicating the presence of intervening lower lake levels around ~10.4-9.4 and ~8.1-6.6 ka. This interpretation is inconsistent with the ODP core 658C terrigenous dust record, which displays no variability in total dust content over this time period (Figure 2). The Gulf of Guinea riverine runoff record indicates extremely wet conditions throughout this period, though centennial scale decreases in runoff are observed in the early Holocene at ~11,000-10,780, 9,450-9,150 and 8,430-8,140 yr BP (32). In contrast, compiled lake level records (6), indicate longer duration reductions in effective moisture levels centered on 12.4, 8.2, 6.6 and 4.0 cal. ka BP. Of these events, the 12.4 ka aridity event is consistent with reduced rainfall during the 12.9-11.5 ka arid phase, whereas the 4.0 ka event may represent drying at the end of the African Humid Period. We interpret the gap between our age clusters at ~10.4-9.4 as indicative of lowered Lake Mega-Chad levels, probably analogous to the 9,450-9,150 cal. years BP reduced runoff event observed in the Gulf of Guinea (1), though we find no evidence for the earlier event. Similarly, the gap between our age clusters at ~8.1-6.6 ka are interpreted as a second phase of lowered Lake Mega-Chad levels. The onset of this event is consistent with the 8,430-8.140 cal. years BP phase in the Gulf or Guinea (32) and the 8.2 cal. ka BP event observed in compiled North African lake records (6), whereas the age cluster starting at 6.6 ka is consistent with the end of the 6.6 ka dry event (6). The cluster of ages between 6.6 and 5.0 ka include a shoreline at 308 m (CH46, 6.0±0.3 ka) which may indicate a brief fall in lake level, consistent with evidence for aridity in nearby regions at this time (33, 34).

4.3. 5 to 3 ka

The youngest secure ages for the 329 m shoreline are ~5 ka, after which the Bodélé lake level falls sufficiently low to allow aeolian dune reactivation in the Bodélé basin at 225 m elevation by 4.7 ± 0.2 ka (24). These data suggest a rapid, centennial scale drying over the Palaeolake Mega-Chad basin after ~5 ka, which is consistent in age with the abrupt end to the African Humid Period reported for East Africa (4860 ± 70 years B.P., (35)), Lake Turkana (5270 ± 300 years B.P., (36)) and northwest Africa (4.9 ± 0.2 ka, (37)). However, both the timing (38) and abruptness of mid-Holocene aridification vary between records of the west/central African Monsoon (39). For example, Gasse (6) indicates rapid drying at 4.0 cal. ka BP, whereas extensive re-dating of the Lake Bosumtwi suggests initial drying at ~5-4 ka, and again at 3,200-3,000 cal. years BP (31) or 2,880 ± 100 cal. years BP (13). In the latter instance, an abrupt sedimentological change is inferred to represent a threshold response to gradual drying of the lake, rather than an abrupt climate change. At Lake Yoa, pollen (3), aquatic community responses (4) and sedimentological and geochemical characteristics (5) suggest gradual drying of the Ounianga region. The pollen assemblages indicate that present-day desert ecosystems were established by 2,700 cal. years BP. Similarly, Gulf of Guinea SSS declines gradually from 5,100 to 360 cal. years BP, indicating slowly reducing runoff from the Niger-Benue and Sanaga rivers (1).

Since the Gulf of Guinea SSS records moisture from Lake Mega-Chad and adjacent catchments during high stands, and Lake Yoa lies within the Bodélé catchment, the discrepancy between these records and that from Lake Mega-Chad requires explanation. A recent re-examination of the Gulf of Guinea SSS record (1) highlights an abrupt decrease in river outflow at 4.9 ka (37), after which SSS increases gradually to the present day. This observation is consistent with the rapid drying of Lake Mega-Chad at c.5 ka, inferred from dune reactivation in the Erg du Djourab at 4.7±0.2 ka (24). In this case, the abrupt increase in Gulf of Guinea SSS at 4.9 ka may be a response to an abrupt reduction in runoff from the Niger-Benue river, which drains a similar latitudinal range to the combined Chad and Bodélé basins. The gradual drying signal observed after 4.9 ka may represent southward migration of the tropical rainbelt (38) causing decreased runoff from more southerly basins, notably the Sanaga and Ntem (30). Consequently, after 4.9 ka, Gulf of Guinea SSS probably records precipitation changes south of the Chad basin. Multiple lines of evidence suggesting progressive drying at Lake Yoa are more difficult to reconcile with our record of abrupt drying of the Lake Mega-Chad catchment, and especially the Bodélé Basin. The abandonment of the 329 m shoreline after 5.0 ka, and reactivation of dunes at 224 m elevation in the Bodélé Basin by 4.7 ± 0.2 ka, indicates an abrupt drop in lake level of >100 m in the Bodélé Basin, and at least 34 m in the Chad Basin, over a few centuries. In addition, the undissected "cordon littoral" of the Angamma Delta indicates that rivers flowing from the Tibesti into the Bodélé Basin from the north had ceased to flow by c.5 ka, while perennial surface water transfer from the Chad Basin via the BEG must have ceased by 4.7 ka, when the Erg du Djourab dunes reactivated. Consequently, it is clear that the Bodélé Basin experienced abrupt desiccation after the end of the most recent Lake Mega-Chad highstand around 5 ka. The Lake Yoa pollen record shows progressive drying from 5,600 cal. years BP, with seasonal river flow from the Tibesti ending around 4,300 cal. years BP (3). We suggest that the Tibesti acted as a water tower, sustaining seasonal river flow into Lake Yoa for a short time after aridification of the rest of the Bodélé Basin. However, this flow was insufficient to dissect the Angamma delta. A semi-desert plant community is evident in the Lake Yoa pollen record between 3,900 and 3,100 cal. years BP, which has been interpreted as an intermediate flora prior to the establishment of true desert plant types (3), though it might also represent pollen input from the Tibesti, acting as an ecological niche under otherwise arid conditions. After 2,700 cal. years BP, the Lake Yoa pollen indicates true desert and Mediterranean plant types. The aquatic community response of Lake Yoa to climate change is complicated by large scale groundwater inputs from the Nubian Sandstone Aquifer (40). The relatively abrupt fresh to saline transition between 3,900 and 3,400 cal. years BP has been explained as a threshold response to progressively reduced groundwater availability (4). However, changes in groundwater discharge volumes would be expected to lag and be buffered relative to changes in aquifer recharge rates (41), so the fresh to saline transition at Lake Yoa is not inconsistent with an abrupt drying across the Bodélé basin at around 5 ka. Consequently, despite their internal consistency, the Lake Yoa records appear to be documenting progressive changes in local conditions rather than the abrupt desiccation experienced by the Bodélé Basin as a whole.

4.4. 3 ka to the present day

Superimposed upon a background of arid conditions in the Lake Mega-Chad basin after 5.0 ka, is a brief 290 m highstand of Lake Chad at 3 ka, which resulted in the deposition of the Ngelewa Ridge. This highstand reached the BEG sill and flooded the Bodélé basin, though resulting in a much smaller volume lake than was present in the early Holocene lake Mega-Chad (Figure 1c). A short-lived return to wetter conditions is recorded across much of the Sahara-Sahel region at this time (6), though timing is quite variable between sites, ranging from ~4.2-3.2 cal. ka BP (39). More northerly records such as ODP core 658C and Lake Yoa do not record this event. At this time, the Bodélé basin would have acted as a powerful moisture sink from Lake Chad, damping lake level response and exporting large quantities of moisture to desert latitudes. It is of interest to note that the Bodélé basin has been proposed as a possible source for the dust found in core 658C (42), though the absence of a decline in terrigenous input to this core at 3 ka demonstrates that this is not the case. After 3 ka, water levels fell in the Bodélé basin, with discharge through the BEG until at least 2.4 ± 0.1 ka and final desiccation after 1.06-0.93 cal. ka BP.

5. Water and dust: The Bodélé basin as a tipping element

The fluctuations of Lake Mega-Chad yield useful information regarding monsoon dynamics, but they also have wider reaching effects upon both the hydrology of northern Africa and nutrient supply to the Equatorial Atlantic and Amazon rain forest. Abrupt oscillations in lake level, particularly in the Bodélé Basin, cause this area to act as both a climatic and biogeochemical “tipping element”. The Bodélé Basin has recently been identified as a tipping element (21) since the presence of erodible diatomite deposited by Lake Mega-Chad, combined with the Bodélé low level jet, make it the World’s greatest single dust source (43-46). Inundation of Bodélé Basin will cause diatomaceous dust emission to cease, leading to changes in cloud physics, direct radiative forcing and distal nutrient supply (21). However, because a detailed record of lake levels in the Bodélé Basin was lacking, the existing analysis (21) primarily considered these effects in relation to present-day processes and potential future climatic change. Here, we use our ~15 ka lake level record to assess the role of the Bodélé Basin as a tipping element, modifying regional climate and modulating dust production and distal nutrient supply.

In northern Africa, the transfer of moisture from equatorial catchments to the Bodélé Basin via the Bahr el Ghazal represents a major, and largely uninvestigated, contribution to the regional hydrological budget. Recent work suggests that the impact of open water surfaces upon mid-Holocene North African climates may have been substantially underestimated in previous climate modeling experiments. For example, it has been suggested that while Lake Mega-Chad locally suppressed precipitation, it increased precipitation by more than 50 % across much of the central and western Sahara (19). In contrast, other workers conclude that the inclusion of Lake Mega-Chad within a model had no effect outside the Chad basin (47). If Lake Mega-Chad does influence precipitation across the central and western Sahara, then the abrupt commencement/termination of moisture export to the Bodélé Basin when Lake Chad reaches the elevation of the BEG sill, represents a major tipping element in regional palaeohydrology. Our lake level reconstruction provides a chronology for the operation of this tipping element.

The export of diatomaceous dust from the Bodélé basin is cited as a potentially important source of limiting nutrients for both the Amazon rain forest and the equatorial Atlantic ecosystems (21, 48-50). However, the exposure of deflatable sediment in the Bodélé basin will have varied, often abruptly, in response to changing lake levels through the Late Pleistocene and Holocene. When the lake bed was dry and surrounded by active dune fields during the LGM, it would almost certainly have been a significant dust source, since both erodible diatomite (51) and active dunes (this paper) were present. Flooding of the Bodélé around 15 ka stopped dust production from these diatomites, which are mainly located in the base of the basin. Deflatable lacustrine sediments in the higher elevation parts of the Bodélé basin may have been periodically exposed, either between the early-mid Holocene highstands or during more severe later drying, allowing mineral dust production. Certainly, records from Nigerian lakes (52) and a west African marine core (53) indicate an increase in dust flux after ~2 ka, which is consistent with our reconstruction of a drying Bodélé basin after 2.4 ± 0.1 ka. It is also possible that higher elevation parts of the Bodélé basin contained diatomite which has now been completely deflated. However, the *in-situ*, articulated bivalves in the base of the Bodélé basin, the location of the majority of exposed diatomite in the present-day, demonstrate that groundwater discharge maintained a standing water body there until at least 1000 years ago. Consequently, these parts of the Bodélé basin, which are the primary source of most of present-day diatomaceous Bodélé dust, remained under water from approximately 15 ka to at least 1 ka. This being the case, the factors which currently make the Bodélé basin the single greatest source of atmospheric dust on Earth (the Bodélé low level jet focused upon diatomite exposed in the lowest elevation parts of the basin, (45)) have only pertained for the last 1000 years. Therefore, the present-day mode and scale of dust production from the Bodélé basin could not have occurred between ~15 and 1 ka. Many studies exclude biogenic contributions from their dust flux calculations (52, 53), thereby removing the main diatomaceous component of present-day Bodélé dust. However, both studies cited above (52, 53) still record an increase in dust flux over the last two millennia, which is consistent with the release of mineral (not diatomaceous) dust from the Bodélé basin in response to drying after 2.4 ± 0.1 ka. Nonetheless, the existence of a small standing water body in the lowest elevation parts of the Bodélé basin would have limited the emission of present day quantities of diatomaceous dust until after 1 ka. Consequently, suggestions that this dust plays an important role in providing limiting nutrients to Amazonian and equatorial Atlantic ecosystems are either overstated, or only true for the last thousand years.

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Author contributions
All authors designed the research and wrote this paper. CSB wrote the RGS-IBG Peter Fleming Award grant application. SJA performed the optically stimulated luminescence dating, CSB interpreted sedimentological data and NAD analysed remotely sensed data.

Figures

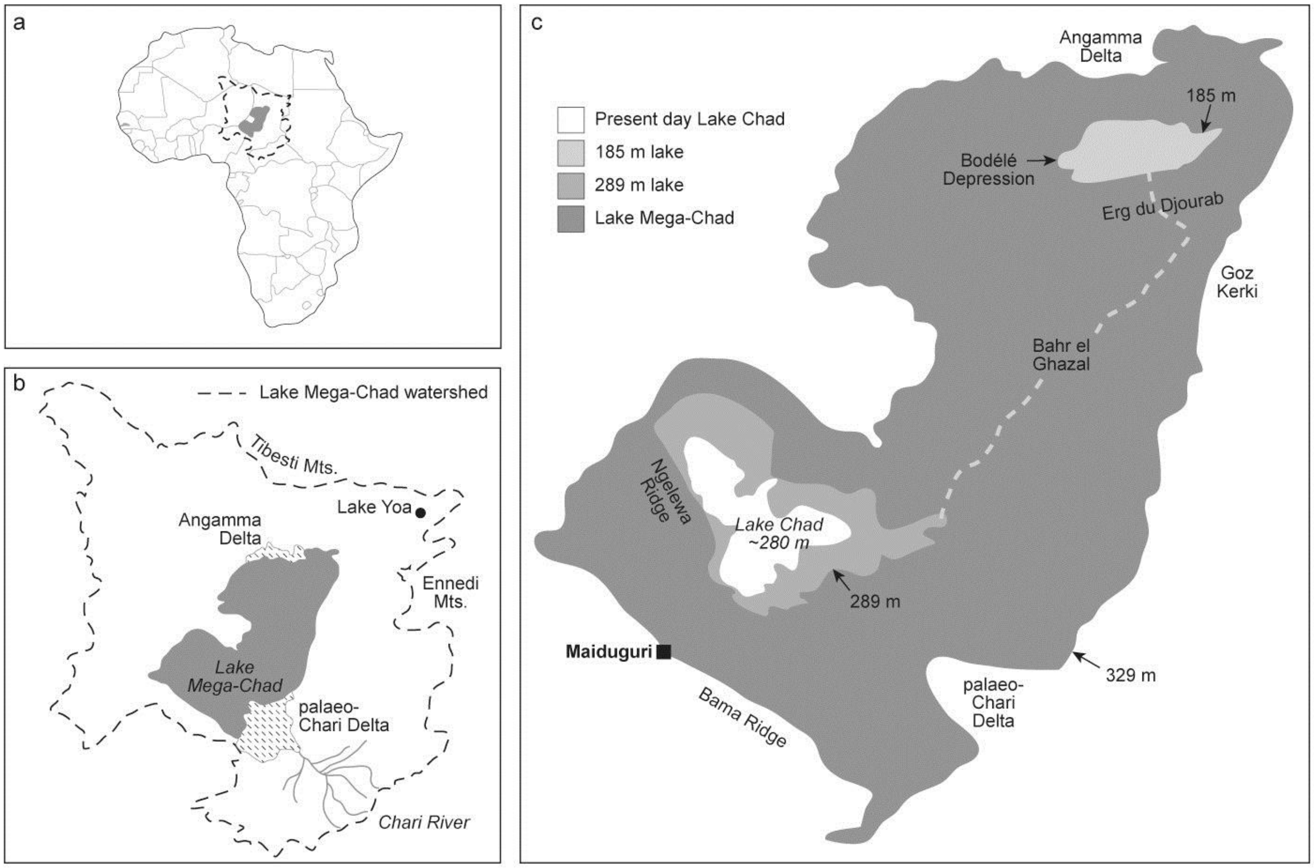

Figure 1. The location and geography of Lake Mega-Chad. a) Location of Lake Mega-Chad and its catchment within Africa. b) Lake Mega-Chad catchment showing the maximum extent of the lake during the Holocene and key geographical features. c) The stages of Lake Mega-Chad identified in this study. The Bhar el Ghazal River (dashed line) that feeds water from Lake Chad into the Bodélé Depression when the level of Lake Chad rises above the sill at 288 m is also shown. The elevations are given in metres above present-day sea-level. The location and elevation of each sample site is shown in more detail in the supplementary information.

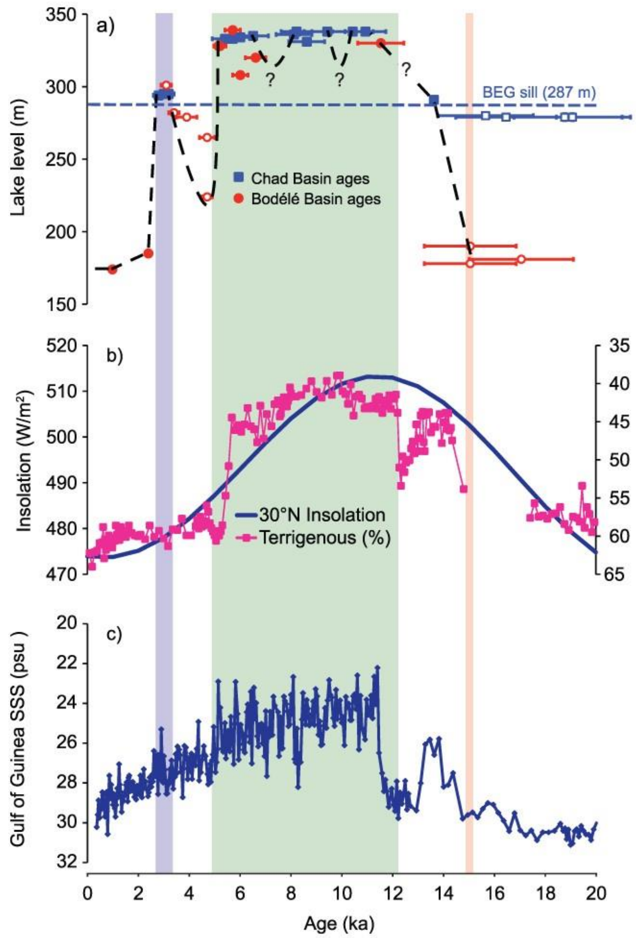

Figure 2. The lake level history of Lake Mega-Chad plotted alongside key West African Monsoon strength records. Data plotting towards the top of the chart indicate wetter conditions. Vertical bars represent key events in the Lake Mega-Chad lake level history. Red - the latest evidence for aeolian dunes on the dry lake bed, green – the main lake highstand and blue - the late Holocene highstand. a) Lake Mega-Chad lake levels. Red data points are from the Bodélé basin, whereas blue ones are from the Chad basin. Open data points represent aeolian sediments, which were deposited above the contemporaneous lake level. Closed data points represent shorelines and therefore contemporaneous lake level. The black dashed line indicates lake-level changes. The horizontal blue dashed line represents the elevation of the BEG sill, below which separate lakes exist in the Chad and Bodélé basins. Consequently lake-level changes below this line represent the Bodélé basin only. Separate lake-level reconstructions for the Chad and Bodélé basins are presented Figure S1. b) 30°N June insolation and ODP core 658C terrigenous dust content (2). c) Gulf or Guinea sea surface salinity (SSS), primarily reflecting discharge from the Niger-Benue and Sanaga rivers, which drain similar latitudes to the Lake Mega-Chad catchment (1).