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The time-transgressive termination of the African Humid Period

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During the African Humid Period about 14,800 to 5,500 years ago, changes in incoming solar radiation during Northern Hemisphere summers led to the large-scale expansion and subsequent collapse of the African monsoon. Hydrologic reconstructions from arid North Africa show an abrupt onset and termination of the African Humid Period. These abrupt transitions have been invoked in arguments that the African monsoon responds rapidly to gradual forcing as a result of nonlinear land surface feedbacks. Here we present a reconstruction of precipitation in humid tropical West Africa for the past 20,000 years using the hydrogen isotope composition of leaf waxes preserved in sediments from Lake Bosumtwi, Ghana. We show that over much of tropical and subtropical Africa the monsoon responded synchronously and predictably to glacial reorganizations of overturning circulation in the Atlantic Ocean, but the response to the relatively weaker radiative forcing during the African Humid Period was more spatially and temporally complex. A synthesis of hydrologic reconstructions from across Africa shows that the termination of the African Humid Period was locally abrupt, but occurred progressively later at lower latitudes. We propose that this time-transgressive termination of the African Humid Period reflects declining rainfall intensity induced directly by decreasing summer insolation as well as the gradual southward migration of the tropical rainbelt that occurred during this interval.

Africa's tropical rainbelt supplies a significant (>60–90%) portion of northern and equatorial Africa's annual moisture, and as a result, changes in the timing or intensity of the seasonal rainfall influence food and water security for more than 150 million people[1]. Future global climate changes are expected to alter the rainbelt[2], but these changes are likely to be complicated by soil moisture, vegetation and albedo feedbacks, which can lead to abrupt, nonlinear changes in vegetation and climate[3–7]. The importance of such feedbacks is particularly evident during the African Humid Period (AHP), a period of higher than modern rainfall across much of West and North Africa between 14,800 and 5,500 yr BP (refs 5,8–11), when gradually increasing Northern Hemisphere summer insolation drove the intensification and northward expansion of the rainbelt[10–12]. Modelling studies demonstrate that this early Holocene intensification is consistent with insolation forcing[8,13], but the magnitude and northward extent of reconstructed hydrologic and vegetation changes can be reproduced only when ocean and land surface feedbacks are included[14,15]. Some models indicate that these feedbacks are capable of producing dynamic instabilities and nonlinear changes in the rainbelt[4,7], a finding supported by proxy data from arid North Africa showing an abrupt onset and termination of the AHP (refs 5,16,17). However, subsequent studies have raised questions about the susceptibility of the tropical rainbelt to nonlinear feedbacks[6,7] and the spatial synchrony of AHP-related changes over North Africa[10], with important consequences for our understanding of past and future hydrologic changes in northern and tropical Africa.

To reassess time–space evolution of the AHP and related changes in moisture over the past 20,000 years, we present a new reconstruction of past hydrologic variations in humid tropical West Africa from the sediments of Lake Bosumtwi, Ghana (Supplementary Figs 1 and 2), We compare this with a synthesis of palaeoclimate records from across northern and tropical Africa, as well as against transient simulations of the African rainbelt from the TraCE-21 experiments (www.cgd.ucar.edu/ccr/TraCE; Supplementary Section 4; ref. 18). The Lake Bosumtwi record provides a unique perspective on climate changes in humid tropical West Africa during the AHP; many of the existing AHP records in this region are either low resolution or discontinuous (see Supplementary Section 1.5 and Fig. 6b) or rely on vegetation reconstructions to infer precipitation, which can be complicated by changes in seasonality[6], land use changes[19] and non-analogue vegetation assemblages[20]. Here, we reconstruct changes in precipitation from the hydrogen isotope composition (δD_{wax}) of leaf waxes (long (C_{31}) straight chain *n*-alkanes; Supplementary Section 2.3), which has been shown to be a reliable indicator of the hydrogen isotope composition of source precipitation in West Africa[21]. As the hydrogen isotopic composition of precipitation in tropical West Africa is controlled mostly by the 'amount effect'[22], δD_{wax} values are interpreted here as indicators of changes in wet season precipitation intensity, following corrections for global ice volume and vegetation type (Supplementary Section 2.3 and Fig. 5). Independent support for the δD_{wax} record comes from an updated reconstruction of palaeolake-level variations at Lake Bosumtwi (Supplementary Section 2.2; ref. 23).

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Long-term trends in δD_{wax} and lake level indicate that the dominant first-order control on West African monsoon variability is Northern Hemisphere summer insolation, with gradually increasing summer insolation driving increased rainfall in the early Holocene[13,14] (Fig. 1). However, the δD_{wax} and lake-level records also demonstrate a strong coupling between monsoon precipitation and high-latitude climate changes during the last deglaciation, with millennial-scale dry intervals associated with periods of enhanced high-latitude cooling and weakened Atlantic meridional overturning circulation[24] during Heinrich stadial 1 (HS1) and the Younger Dryas event (Fig. 1). The magnitude of the δD_{wax} increase during HS1 indicates that this was the driest interval of at least the past 20,000 years, consistent with the evidence for exceptionally dry conditions throughout the northern tropics at this time[25]. Inferred deglacial precipitation changes are also in agreement with the results from the TraCE-21 transient climate experiment (Fig. 1d and Supplementary Section 4). For both HS1 and the Younger Dryas, meltwater-induced reductions in North Atlantic sea surface temperatures result in a negative sea-level pressure anomaly over the Sahara and a southward shift of the African easterly jet, producing a southward shift in the monsoon rainbelt and a widespread reduction in the intensity of summer rainfall. The onset and recovery during HS1 and the Younger Dryas are rapid and synchronous within age model uncertainties between the model output, the Lake Bosumtwi reconstruction and records from across North Africa, confirming that large-scale reorganizations of the African rainbelt can occur rapidly in association with millennial-scale North Atlantic forcing and persistent, continent-wide drought.

Unlike the deglacial, the Holocene portion of the Lake Bosumtwi record suggests a complex precipitation response to changing Northern Hemisphere summer insolation. Wet conditions peaked between 11,060 ± 520 and 9,360 ± 150 cal. yr BP and decreased gradually over the early to middle Holocene (8,480 ± 100 to 5,560 ± 110 cal. yr BP) following changes in Northern Hemisphere summer insolation. These changes are consistent with Holocene proxy climate reconstructions from the Indian[26], Asian[27] and South American[28] monsoon systems together with model predictions of a dominant, insolation-driven control over the tropical rainbelt during the Holocene[3,8,13]. However, the δD_{wax} data from Lake Bosumtwi suggest that the insolation-driven gradual trend towards drier conditions was interrupted by an abrupt increase in precipitation at 5,410 ± 80 cal. yr BP, which persisted until 3,170 ± 70 cal. yr BP and delayed the end of the AHP by several thousand years.

A tropical West African perspective on the AHP

Changes at Lake Bosumtwi differ from both the abrupt termination of the AHP at 5,590 ± 30 yr BP in North Africa[5], and the results of the TraCE-21 experiments that suggest a longer but less intense early Holocene wet period (10,000–6,000 yr BP) and a gradual decline in rainfall to present. However, Lake Bosumtwi is not alone in suggesting a complex precipitation response to insolation forcing. Early to mid-Holocene drying after about 9,000 cal. yr, followed by an abrupt return to wet conditions between about 6,000–3,000 cal. yr is also evident in hydrogen isotope records from both offshore Senegal (15.5° N; ref. 29) and the Congo Fan (5° N; ref. 30; Fig. 2). Together, these records suggest that this is a consistent large-scale feature of the late Holocene within the monsoon sector, and potentially the tropical rainbelt over Africa as a whole. However, the occurrence of this late Holocene precipitation increase seems to have been time-transgressive with wet conditions reappearing earliest in Senegal (for example, 7,100 ± 750 cal. yr BP), later at Bosumtwi (5,410 ± 80 cal. yr) and last at the Congo Fan (2,940 ± 860 cal. yr). These differences in timing are well outside the age model uncertainties of these records.

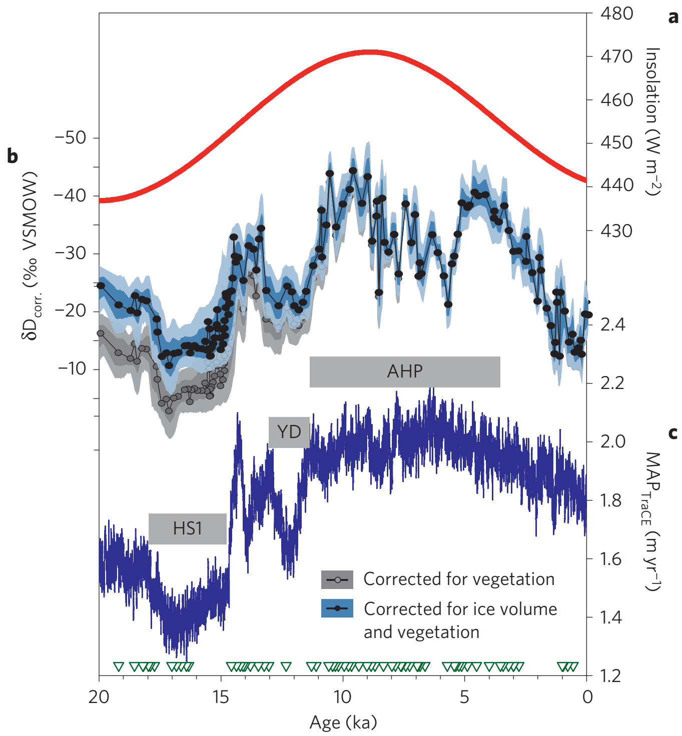

Figure 1 | Comparison of proxy and model estimates of hydrologic variations at Lake Bosumtwi. a, June–August insolation changes at 6.5° N (ref. 37). **b**, Hydrogen isotope composition of C_{31} *n*-alkanes adjusted for changes in vegetation (grey) and vegetation and ice volume (blue; Supplementary Methods 1.4.3), indicating changes in precipitation. Shading reflects 66% (dark) and 95% (light) uncertainties in the reconstruction, based on analytical and age model errors. $\delta D_{corr.}$; δD_{wax} corrected for vegetation and ice volume. **c**, Mean annual precipitation for the model gridbox containing Lake Bosumtwi from the TraCE-21 simulations[18] (Supplementary Section 1.6). Green triangles denote radiocarbon dates used in the Lake Bosumtwi age model. YD, Younger Dryas.

This is consistent with a southward migration of the monsoon rainbelt over the mid- to late Holocene. Today, on interannual to decadal timescales, precipitation varies owing to both monsoon intensity and latitudinal migration of the rainbelt. Variations in monsoon intensity result in coherent changes in rainfall throughout the region, whereas the seasonal migration of the rainbelt results in a north–south precipitation dipole, with out-of-phase variations in rainfall between arid and humid Africa[31]. The latter is mostly due to seasonality; a northward shift in the rainbelt results in greater moisture delivery at its northern limit during the summer, but is accompanied by lower rainfall to the south because of a longer summer dry season (Supplementary Fig. 2). During the early Holocene, as the seasonal limit of the rainbelt retreated southward in response to weakening insolation, this optimal balance between total moisture delivery and summer dry season length would have occurred progressively later at lower latitudes, resulting in a time-transgressive, secondary rainfall maxima occurring later at lower latitude sites, as evident in the proxy data (Fig. 2).

In sites from the Sahara, at or beyond the northern limit of the modern-day monsoon, the response is different[5,16,17]. Even at the height of the AHP these sites probably received moisture during only a few months of the summer, when the monsoon reached its absolute northernmost limit (Supplementary Fig. 8). As a result, even a small southward shift in the northernmost position of the monsoon rainbelt would have resulted in a substantial decrease in the amount of rainfall and a rapid disappearance of vegetation[6]. This is consistent with the evidence for an abrupt decline in

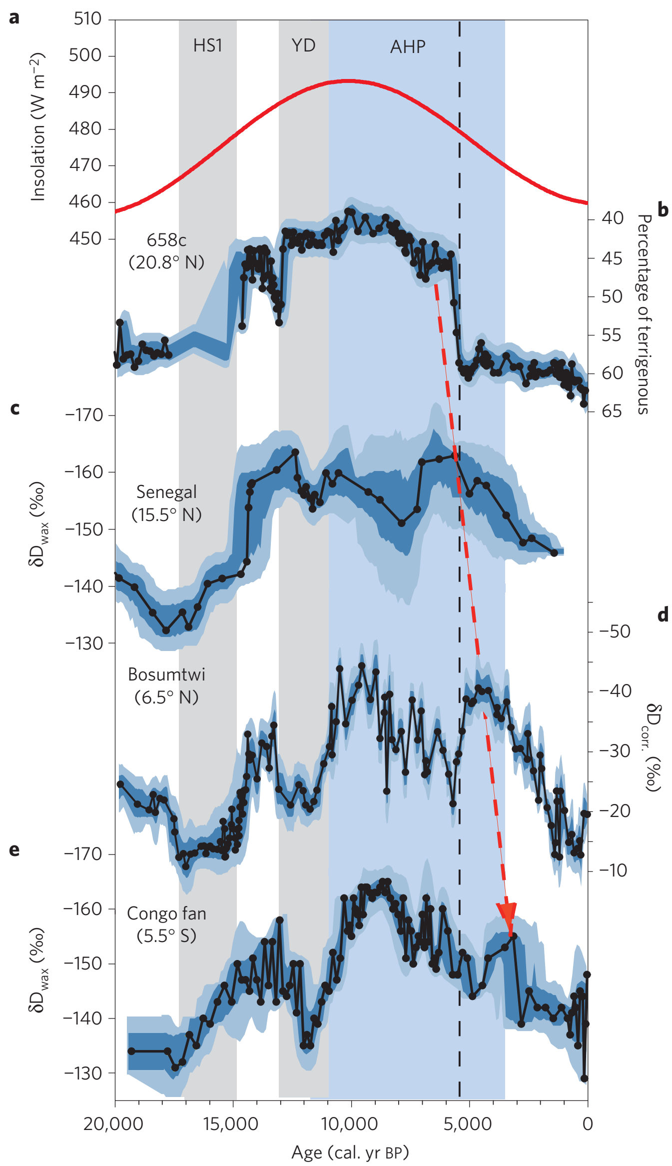

Figure 2 | Proxy records of West African monsoon variability over the past 20,000 years. a, June–August insolation at 30° N (ref. 37). **b**, North African dust flux (ODP 658c; 20° 45′ N, 18° 35′ W; ref. 5). **c**–**e**, δD_{wax} from the Senegal River (GeoB9508-5; 15° 30′ N, 17° 57′ W; ref. 29; **c**), Lake Bosumtwi (6° 30′ N, 1° 25′ W; **d**) and the Congo Fan (GeoB6518; 5° 35′S, 11° 13′ E; ref. 30; **e**). Shading reflects 66% (dark) and 95% (light) uncertainties. Vertical bars indicate HS1, Younger Dryas (YD) and the AHP. Black dashed line indicates the end of the AHP in North Africa[5]. The red arrow indicates the inferred delayed southward shift of the rainbelt.

precipitation or vegetation, but does not require nonlinear land surface–monsoon feedbacks[6].

Onset and termination of the AHP across northwest Africa

Although some of the existing proxy records from Africa may not have the resolution or sensitivity needed to reconstruct mid-Holocene climate variability, we predict that a consequence of this southward shift in the rainbelt should be the progressively later termination of the AHP at lower latitude sites across the continent. To evaluate this hypothesis, we synthesized existing palaeohydrologic data from across northern and tropical Africa over the past 20,000 years (Fig. 3 and Supplementary Section 1.5). These sites cover most of Africa, and span variable precipitation regimes, but all are impacted by the African rainbelt. For completeness, we include sites from East Africa in our synthesis, although we note that the controls on East African rainfall are complex and probably include influences from Indian Ocean sea surface temperature variations, which may cause rainfall variations at these sites to deviate from those of West and Central Africa[17].

Although data on the onset of the AHP are sparse, our synthesis indicates that wet conditions began almost everywhere immediately after H1 (14,000–15,000 yr BP); however, maximum humidity was not achieved until the early Holocene because of a return to more arid conditions during the Younger Dryas event. In contrast, the termination of the AHP, although variable, consistently occurred later over much of subtropical to tropical West and Central Africa (<15° N; 2,500–4,000 yr BP) than at sites north of the modern-day monsoon system limit (>15° N; 5,000–6,000 yr BP; Fig. 3a). These results are consistent with proposed mechanisms: large deglacial forcings associated with changes in Atlantic sea surface temperatures and greenhouse gases synchronized precipitation changes across Africa at the onset of the AHP (ref. 32), whereas weaker, insolation-driven forcing in the mid-Holocene led to a more complex and time-transgressive response at the end of the AHP. Furthermore, our synthesis suggests that this asynchronous response was not restricted to West and Central Africa; the data also suggest an east–west gradient in the termination of the AHP, which could reflect the relatively greater influence of the Indian Ocean on East African climate variability during the Holocene (Supplementary Fig. 7b).

The results of the TraCE experiment do not show either the abrupt changes in precipitation recorded in North African dust records or the out-of-phase precipitation changes evident in Lake Bosumtwi and other proxy climate records during the mid- to late Holocene. Instead, they show increased precipitation between 10,000 and 6,000 yr BP followed by a gradual decrease over the remainder of the Holocene. Above, we proposed that an extended and more intense summer dry season during the early to mid-Holocene (9,000–5,000 yr BP) played a critical role in driving these changes. The TraCE-21 experiment did not simulate any summer dry season along the Guinea Coast throughout the Holocene (Supplementary Fig. 8), let alone the enhanced dry seasons that we suggest accompanied northward expansion of the rainbelt during the early Holocene. Importantly, our results suggest that these effects were crucial in the evolution of precipitation changes during the Holocene. The deviation from observed climatology, which is a common problem in global climate models[33], probably explains the data–model mismatch. In the absence of a very large climate (for example, glacial) forcing, or in instances where rainfall variations are the result of changes in the position of the rainbelt rather than its intensity, existing models may not adequately capture variations in the African rainbelt.

Regionally time-transgressive termination of the AHP

Placed in the context of change across northern and tropical Africa over the past 20,000 years, our new reconstruction from Lake Bosumtwi provides an updated view of the AHP that is quite different from that derived from a well-cited record of abrupt precipitation changes in arid North Africa[5]. Although the end of the AHP is locally abrupt, suggesting a nonlinear evolution of precipitation changes in response to gradually changing insolation, the timing and duration of this wet–dry transition varies spatially, and is inconsistent with a single abrupt collapse of the African monsoon in response to nonlinear land surface–monsoon feedbacks. Either the early, abrupt changes identified previously in dust records from North Africa were the result of local vegetation threshold effects on dust production, as suggested by some models[6], or the influence of feedbacks causing abrupt monsoon shifts was dominant only at the very northernmost limit of the monsoon system. Regardless, a mid-Holocene (that

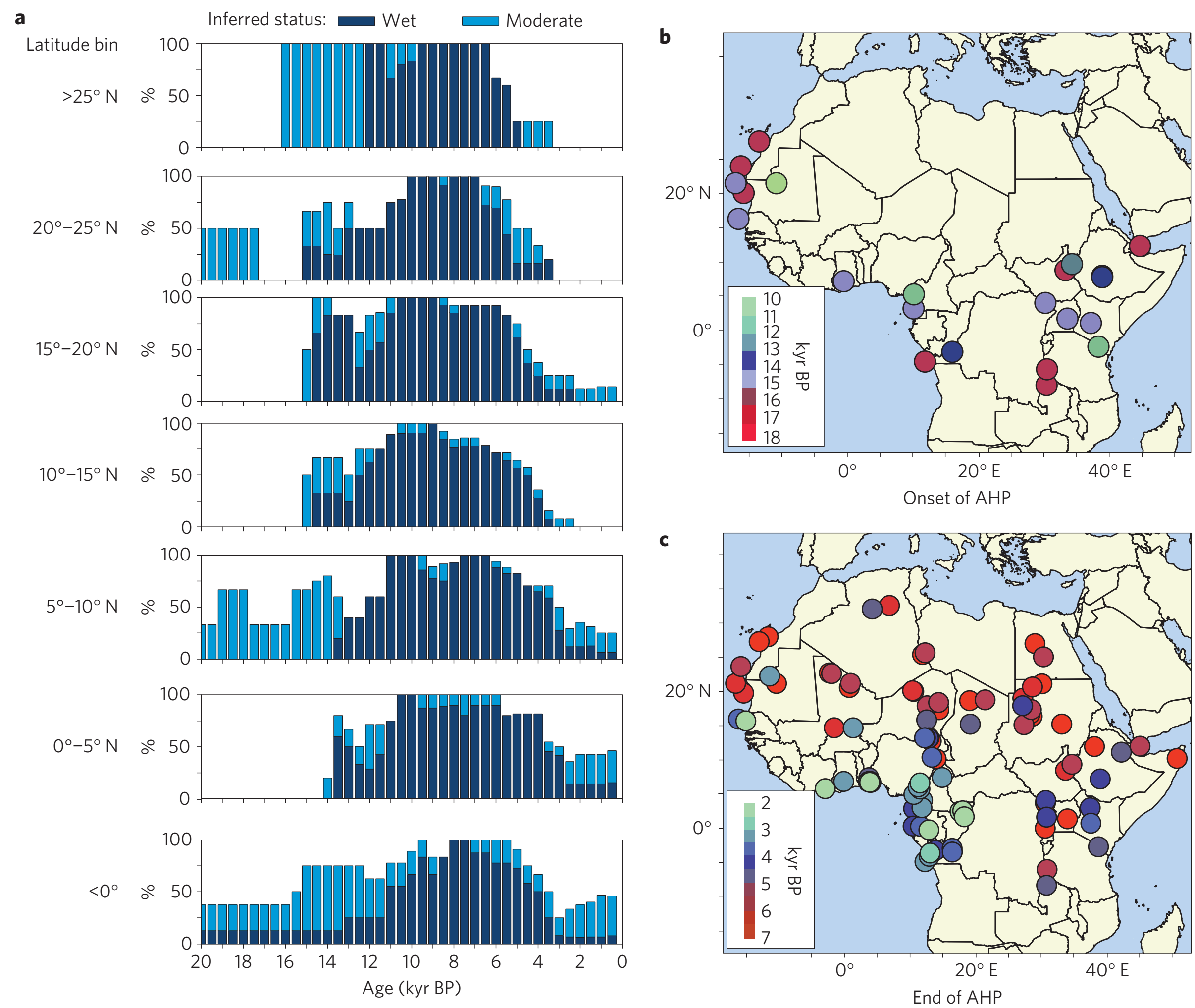

Figure 3 | Hydrologic changes across North Africa over the past 20,000 years. a, Frequency histograms for all records shown indicating wet or intermediate conditions, binned at 5° latitude intervals. The results are nearly identical when the sites from East Africa are excluded (Supplementary Fig. 7a). **b**,**c**, Maps of the timing of changes in water balance at the beginning and end of the AHP. A clockwheel map and an animation of water balance changes are also available in Supplementary Fig. 6b,c. See Supplementary Section 1.5 and Table 1 for site details and references.

is, 5,500 cal. yr) abrupt shift in the monsoon is not the primary feature of Holocene hydrologic changes over most of northern Africa. Instead, the evolution of mid- to late Holocene hydrologic changes reflects a combination of declining rainfall intensity driven directly by decreasing summer insolation and a southward shift of the northernmost seasonal limit of the monsoon rainbelt, with the latter effect resulting in a time-transgressive southward shift in the termination of the AHP.

Over most of northern and tropical Africa, understanding the monsoon response to radiative forcing must consider changes in both the position and intensity of the monsoon, which result in rainfall variations that may seem abrupt at the more regional or local scale, but that are actually time-transgressive at the sub-continental scale. Conversely, the synchronous reduction in rainfall over large parts of North Africa during rapid millennial episodes of deglacial North Atlantic sea surface cooling (Figs 2 and 3) highlights the fact that synchronous and abrupt change can occur on continental scales, but only if the climate forcing is large and results in changes in monsoon intensity. Climate models are capable of simulating these continent-wide synchronous responses to large forcing: the TraCE-21 experiment reproduces the monsoon response to North Atlantic forcing well (Fig. 1). However, the simulations do not reproduce the observed out-of-phase variability in precipitation between the northern limit of the rainbelt and lower latitudes between 8,000 and 2,500 cal. yr because of their inability to properly simulate the seasonal cycle of rainfall. Future climate forcing, although substantial, is likely to be more modest and of the order of insolation forcing during the Holocene[34]. This relationship between the magnitude of climate forcing and the spatial scale of climate response poses a challenge for modelling future moisture variability because the response is more likely to involve asynchronous behaviour poorly reproduced in models. Adaptation planning for the sub-Saharan region should thus include provisions for locally abrupt changes in future precipitation that might nevertheless be asynchronous across the region.

Methods

Lake sediments were solvent extracted using either a Dionex accelerated solvent extractor or a CEM MARS X microwave extraction system with dichloromethane/methanol (9:1; v/v). Saturated hydrocarbons were isolated for stable isotope analysis using silica flash chromatography with hexane and methanol followed by $AgNO_3$ chromatography and molecular sieve or urea adduction. Hydrogen isotope analysis of individual *n*-alkanes was performed using a gas chromatograph equipped with a DB-5 ms column ($30\,m \times 0.25\,\mu m \times 0.25\,mm$), coupled to a Delta V isotope ratio mass spectrometer through a pyrolysis interface operated at 1,430 °C. Isotope values were measured against calibrated propane reference gas and are reported in ‰ Vienna Standard Mean Ocean Water (VSMOW). Additional technical details are available in the Supplementary Information.

A chronology for the lake sediment record is based on Bayesian age–depth modelling of 107 radiocarbon ages using the R-program software BACON (refs 35,36). Palaeolake-level constraints are based on radiocarbon dating of palaeobeaches, terraces and exposed lacustrine silts throughout the crater[23]. Constraints on the crater overflow are based on radiocarbon dating of a high terrace and cosmogenic surface exposure dating of an erosional spillway notch in the crater rim[23]. More details are provided in the Supplementary Information.

Data. The hydrogen isotope data from Lake Bosumtwi are available at http://www.ngdc.noaa.gov.

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References

1. Boko, M. *et al.* in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. *et al.*) 433–467 (IPCC, Cambridge Univ. Press, 2007).
2. Patricola, C. M. & Cook, K. H. Sub-Saharan Northern African climate at the end of the twenty-first century: Forcing factors and climate change processes. *Clim. Dynam.* **37,** 1165–1188 (2011).
3. Braconnot, P. *et al.* Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum—Part 2: Feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget. *Clim. Past* **3,** 279–296 (2007).
4. Claussen, M. *et al.* Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. *Geophys. Res. Lett.* **26,** 2037–2040 (1999).
5. DeMenocal, P. *et al.* Abrupt onset and termination of the African Humid Period: Rapid climate responses to gradual insolation forcing. *Quat. Sci. Rev.* **19,** 347–361 (2000).
6. Liu, Z. *et al.* Simulating the transient evolution and abrupt change of Northern Africa atmosphere–ocean–terrestrial ecosystem in the Holocene. *Quat. Sci. Rev.* **26,** 1818–1837 (2007).
7. Renssen, H., Brovkin, V., Fichefet, T. & Goosse, H. Simulation of the Holocene climate evolution in Northern Africa: The termination of the African Humid Period. *Quat. Int.* **150,** 95–102 (2006).
8. Kutzbach, J. E. & Otto-Bliesner, B. The sensitivity of the African–Asian monsoon climate to orbital parameter changes for 9000 years BP in a low-resolution general circulation model. *J. Atmos. Sci.* **39,** 1177–1188 (1982).
9. Street-Perrott, F. A. & Perrott, R. A. Abrupt climate fluctuations in the tropics: The influence of Atlantic Ocean circulation. *Nature* **343,** 607–612 (1990).
10. Lezine, A. M., Hely, C., Grenier, C., Braconnot, P. & Krinner, G. Sahara and Sahel vulnerability to climate changes, lessons from Holocene hydrological data. *Quat. Sci. Rev.* **30,** 3001–3012 (2011).
11. Gasse, F. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quat. Sci. Rev.* **19,** 189–211 (2000).
12. Prentice, I. C. & Jolly, D. Mid-Holocene and glacial-maximum vegetation geography of the northern continents and Africa. *J. Biogeogr.* **27,** 507–519 (2000).
13. Kutzbach, J. E. & Street-Perrot, F. A. Milanovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP. *Nature* **317,** 130–134 (1985).
14. Kutzbach, J. E. & Liu, Z. Response of the African monsoon to orbital forcing and ocean feedbacks in the middle Holocene. *Science* **278,** 440–443 (1997).
15. Levis, S., Bonan, G. B. & Bonfils, C. Soil feedback drives the mid-Holocene North African monsoon northward in fully coupled CCSM2 simulations with a dynamic vegetation model. *Clim. Dynam.* **23,** 791–802 (2004).
16. McGee, D., Demenocal, P. B., Winckler, G., Stuut, J. B. W. & Bradtmiller, L. I. The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000yr. *Earth Planet. Sci. Lett.* **371–372,** 163–176 (2013).
17. Tierney, J. E. & deMenocal, P. B. Abrupt shifts in Horn of Africa hydroclimate since the Last Glacial Maximum. *Science* **342,** 843–846 (2013).
18. Liu, Z. *et al.* Transient simulation of last deglaciation with a new mechanism for Bolling-Allerod warming. *Science* **325,** 310–314 (2009).
19. Brncic, T. M., Willis, K. J., Harris, D. J. & Washington, R. Culture or climate? The relative influences of past processes on the composition of the lowland Congo rainforest. *Phil. Trans. R. Soc. B* **362,** 229–242 (2007).
20. Watrin, J., Lezine, A-M. & Hely, C. Plant migration and plant communities at the time of the "green Sahara". *C. R. Geosci.* **341,** 656–670 (2009).
21. Garcin, Y. *et al.* Hydrogen isotope ratios of lacustrine sedimentary *n*-alkanes as proxies of tropical African hydrology: Insights from a calibration transect across Cameroon. *Geochim. Cosmochim. Acta* **79,** 106–126 (2012).
22. Lutz, A., Thomas, J. M. & Panorska, A. Environmental controls on stable isotope precipitation values over Mali and Niger, West Africa. *Environ. Earth Sci.* **62,** 1749–1759 (2011).
23. Shanahan, T. M., Overpeck, J. T., Sharp, W. E., Scholz, C. A. & Arko, J. A. Simulating the response of a closed-basin lake to recent climate changes in tropical West Africa (Lake Bosumtwi, Ghana). *Hydrol. Process.* **21,** 1678–1691 (2007).
24. McManus, J. F., Francois, R., Gherardi, J. M., Keigwin, L. D. & Brown-Leger, S. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* **428,** 834–837 (2004).
25. Stager, J. C., Ryves, D. B., Chase, B. M. & Pausata, F. S. R. Catastrophic drought in the Afro-Asian monsoon region during Heinrich event 1. *Science* **331,** 1299–1302 (2011).
26. Fleitmann, D. *et al.* Holocene forcing of the Indian monsoon recorded in a stalagmite from Southern Oman. *Science* **300,** 1737–1739 (2003).
27. Wang, Y. *et al.* The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science* **308,** 854–857 (2005).
28. Haug, G., Hughen, K., Sigman, D., Peterson, L. & Rohl, U. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293,** 1304–1308 (2001).
29. Niedermeyer, E. M. *et al.* Orbital- and millennial-scale changes in the hydrologic cycle and vegetation in the western African Sahel: Insights from individual plant wax δD and δ^{13}C. *Quat. Sci. Rev.* **29,** 2996–3005 (2010).
30. Schefuß, E., Schouten, S. & Schneider, R. Climatic controls on central African hydrology during the past 20,000 years. *Nature* **437,** 1003–1006 (2005).
31. Nicholson, S. E. The nature of rainfall variability over Africa on time scales of decades to millenia. *Glob. Planet. Change* **26,** 137–158 (2000).
32. Otto-Bliesner, B. L. *et al.* Coherent changes of southeastern equatorial and northern African rainfall during the last deglaciation. *Science* (in the press; 2014).
33. Vizy, E. K., Cook, K. H., Crétat, J. & Neupane, N. Projections of a Wetter Sahel in the twenty-first century from global and regional models. *J. Clim.* **26,** 4664–4687 (2013).
34. Christensen, J. H. *et al.* in *Climate Phenomena and their Relevance for Future Regional Climate Change* (eds Stocker, T. F. *et al.*) 1217–1308 (IPCC, Cambridge Univ. Press, 2013).
35. Blaauw, M. & Christen, J. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analsis* **6,** 457–474 (2011).
36. Shanahan, T. M. *et al.* 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 (2012).
37. Laskar, J. *et al.* A long term numerical solution for the insolation quantities of the Earth. *Astron. Astrophys.* **428,** 261–285 (2004).

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Author contributions

Palaeolake-level reconstructions were carried out by T.M.S. and J.T.O. Biomarker analysis was performed by T.M.S. and K.A.H. Analysis of TraCE-21 simulations was conducted by N.P.M. and B.O-B. Field work was conducted by T.M.S., J.T.O., J.P., C.W.H., J.K. and C.A.S. Interpretation was carried out by T.M.S., N.P.M., J.T.O. and K.A.H.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.M.S.

Competing financial interests

The authors declare no competing financial interests.