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Atlantic Forcing of Persistent Drought in West Africa

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Although persistent drought in West Africa is well documented from the instrumental record and has been primarily attributed to changing Atlantic sea surface temperatures, little is known about the length, severity, and origin of drought before the 20th century. We combined geomorphic, isotopic, and geochemical evidence from the sediments of Lake Bosumtwi, Ghana, to reconstruct natural variability in the African monsoon over the past three millennia. We find that intervals of severe drought lasting for periods ranging from decades to centuries are characteristic of the monsoon and are linked to natural variations in Atlantic temperatures. Thus the severe drought of recent decades is not anomalous in the context of the past three millennia, indicating that the monsoon is capable of longer and more severe future droughts.

Beginning in the late 1960s, much of West Africa experienced severe drought, which peaked in the mid-1970s and lasted for several decades, displacing millions from sub-Saharan Africa (*1*). Since that time, concerted efforts by climatologists, geologists, and modelers have focused on understanding the factors controlling West African monsoon (WAM) variability (*2*–*6*). Much of this research now implicates changing sea surface temperatures (SSTs) in generating long-lasting wet and dry periods, with positive land surface feedbacks exacerbating these changes (*3*–*5*). However, it is uncertain whether recent multidecadal drought is anomalous in the context of late Holocene climate variability, because long instrumental records and high-resolution paleoclimate reconstructions from the African tropics are lacking (*5*).

We generated a near-annual record of West African hydrologic variability, using annually laminated sediment cores from Lake Bosumtwi, Ghana (6°30′N, 1°25′W) (*7*). Lake Bosumtwi is ideally suited to reconstructing variations in the WAM because of its location in humid tropical West Africa and because its sediment laminations provide a high-resolution chronology for the paleoclimatic record (*7*, *8*). Hydrologic changes were reconstructed using oxygen isotopes of authigenic lake carbonate and micro–x-ray fluorescence (μ-XRF) scanning of major element concentrations (*7*). Authigenic carbonate $\delta^{18}O$ reflects that of Bosumtwi lake water, which, because the lake is a closed basin, is linked to the balance between precipitation and evaporation. This interpretation is supported by the correlation ($R_{49} = 0.55$, $P < 0.001$) between changes in precipitation measured instrumentally and high-resolution (at 2- to 5-year sampling intervals) carbonate $\delta^{18}O$ variations in the sediment record (Fig. 1). Although the proxy data reproduce variations in local precipitation on decadal time scales, the relationship is weaker on interannual time scales. These differences most likely reflect both the spatially heterogeneous nature of monsoon rainfall on interannual time scales (*8*) and the practical difficulties in precisely subsampling laminae from highly flocculant near-surface sediments. Although differences exist in the magnitude and timing of low-frequency rainfall variability across West Africa, including an apparent delayed onset of late 20th-century drought near the coast and a variable dry period in 1941–1949, quite similar decadal variability is apparent in instrumental records from throughout the monsoon region (fig. S1). This demonstrates that local rainfall reconstructions, such as that from Lake Bosumtwi, may be used to infer regional-scale changes in monsoon precipitation on decadal and longer time scales.

Variations in sediment elemental concentrations are interpreted as reflecting changes in the flux of terrigenous material to the lake during the summer monsoon. This flux is controlled by the size of the erodable catchment area, with higher elemental concentrations occurring during low lake levels, when more of the crater is emergent and the erodable catchment area is larger. High-resolution (20- to 40-μm) XRF scanning of intact sediment cores provides major element concentrations at subannual resolution, allowing the reconstruction of annual to decadal climate variability, which is not possible with $\delta^{18}O$ because of variable carbonate preservation (*7*). Here we focus on the first principal component (PC1) of the full suite of elemental data (Al, Si, K, Ca, Ti, Mn, and Fe) as a proxy for the terrigenous sediment component of the record. The similarities between variations in carbonate $\delta^{18}O$ and PC1 further support our interpretation of the XRF data as an indicator of lake status (supporting online text).

Additional support for our interpretation of the geochemical data comes from geological evidence for past lake levels (*9*, *10*). Low elemental concentrations (more positive PC1) and more negative isotopic signatures in the early part of the record are consistent with evidence for mid-Holocene lake deposits up to 100 m above the modern lake surface (*9*). Stromatolite-encrusted terraces at 20 to 25 m above the modern lake level formed between

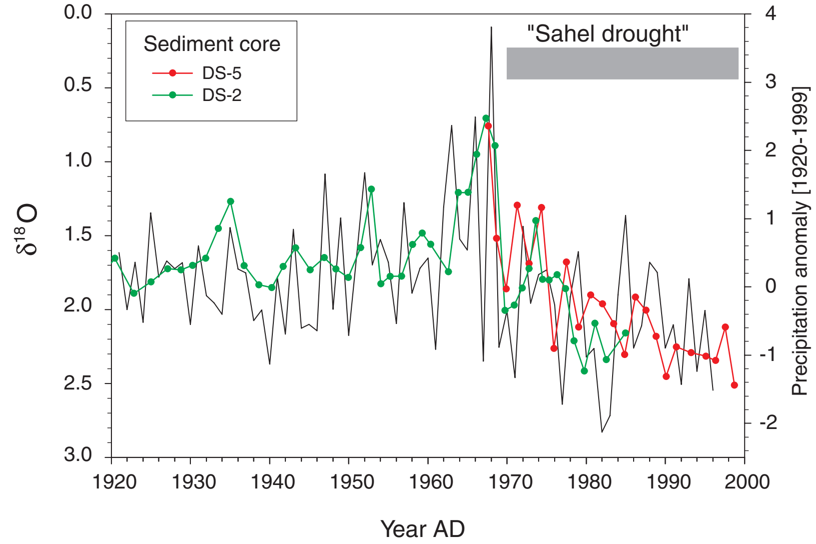

Fig. 1. Proxy instrumental data comparison of rainfall variability in West Africa. Carbonate oxygen isotope data (circles and colored lines) from cores DS-2 and DS-5, placed on a laminae age model plotted with normalized precipitation anomalies from the Kumasi meteorological station (black line), 35 km northwest of the lake, are shown. More negative isotopic values occur during intervals with high precipitation rates ($r = 0.55$, significant at 95%). Both records show the interval of enhanced precipitation before ~1965 and a dramatic dropoff in precipitation after 1970. This shift in rainfall is synchronous with a well-documented period of extended drought in the Sahel region of North Africa (10° to 20°N, 20°W to 40°E) known as the Sahel drought (gray horizontal bar).

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~2200 and ~1650 years before the present (yr B.P.), reflecting a positive water balance at that time, are also consistent with sediment core data (Fig. 2) (*9*). Two late Holocene lowstands are also evident in high-resolution seismic reflection data, suggesting lake level drops of 31 and 24 m at ~700 to 1000 and 250 to 500 calendar yr B.P., respectively (*10*), in agreement with the timing of the largest lowstands in the sediment core data.

Sediment geochemical data indicate that Lake Bosumtwi underwent a progressive drying between 2660 and ~1000 yr B.P., with the most rapid drying occurring after ~1700 to 1800 yr B.P. (Fig. 2A). This long-term trend is consistent with climate simulations (*11*, *12*) and paleoclimate reconstructions (*13*–*17*), which support a weakening of the WAM in response to gradually decreasing summer insolation over the late Holocene. Superimposed on this trend are a series of multi-century droughts. The most recent of these occurred between 1400 and 1750 CE (550 to 200 yr B.P.), similar in timing to the Little Ice Age (LIA, ~1400 to 1850 CE), a well-known interval when Northern Hemisphere temperatures were cooler than at present (*18*). In contrast with earlier studies, which reconstructed wetter conditions in East Africa during this period (*19*), evidence from Lake Bosumtwi supports more recent studies suggesting that this interval was dry (*20*, *21*). Evidence for LIA drought is not restricted to Africa, however. Records from throughout the tropics, including the western Pacific warm pool (*22*), the Arabian Sea (*23*, *24*), continental Asia (*25*), and tropical South America (*26*) all show evidence for dry conditions during this time period. Wet conditions in West Africa during the few centuries preceeding (~1200 to 1400 CE) and following (~1800 CE to the present) this dry interval are also apparent in a number of tropical monsoon records (Fig. 3) (*21*, *23*–*25*), forming a coherent pattern of variability that indicates common large-scale forcing of tropical climate over the past millennium.

These alternating wet and dry conditions form part of a longer pattern of centennial-scale variability in the WAM that spans the late Holocene (Fig. 2A). Multi-taper method (MTM) spectral analysis (*27*) of the XRF data confirms the importance of this mode, with broad areas of significant power centered around 90, 160 to 190, 200 to 240, and >300 years (Fig. 4A). Their statistical significance was confirmed by wavelet spectral analysis (*28*), which displays a maximum in power at century time scales throughout the record (Fig. 2B), and by singular spectrum analysis (SSA), with reconstructed components (RCs) of similar, though not identical, mean periods (RC1 to RC2, 360 to 390 and 500 years; RC3 to RC4, 205 to 220 years) (*29*). Based on similarities with the record of atmospheric Δ^{14}C, a proxy for past solar variability (*30*), previous authors have attributed centennial variability in tropical paleoclimate records to changes in solar irradiance (*23*–*25*). However, there are no clear correlations between centennial variability in the Bosumtwi record and changes in atmospheric Δ^{14}C, indicating that, at least in West Africa, the sun-climate link is weak or indirect. One possibility is that centennial variability in continental West Africa is generated by internal oscillations in the tropical Atlantic ocean-atmosphere system (*31*). Simulations of the Atlantic meridional overturning circulation (AMOC) with the HadCM3 coupled ocean-atmosphere model suggest that interactions between the intertropical convergence zone (ITCZ) and the AMOC can generate centennial-scale climate changes internal to the tropical Atlantic climate system (*32*). Because of the direct effect of ITCZ migrations on the WAM, these changes could dominate rainfall variability over West Africa on these time scales and might overwhelm the influence of any external forcing mechanism such as solar irradiance. The AMOC connection also provides a means of connecting changes in the WAM to changes in the high latitudes and elsewhere in the tropics.

Spectral analysis (*27*) indicates that there is also significant power at annual (3.6-to 4.6-year), decadal (7.1- to 13.8-year), and multidecadal (33- to 42-year) bands (Fig. 4A). Variability at 3- to 5-year periods may be linked to either the remote influence of Pacific El Niño events [typically at 2- to 7-year intervals (*33*)] or zonal SST variations in the tropical Atlantic [Atlantic El Niños, 2- to 2.5-year intervals (*34*)], both of which are known to affect the modern WAM. The decadal variability is similar to that of Atlantic trade wind variations (8.7- to 9.0-year and 12.5- to 13-year) reconstructed from Cariaco

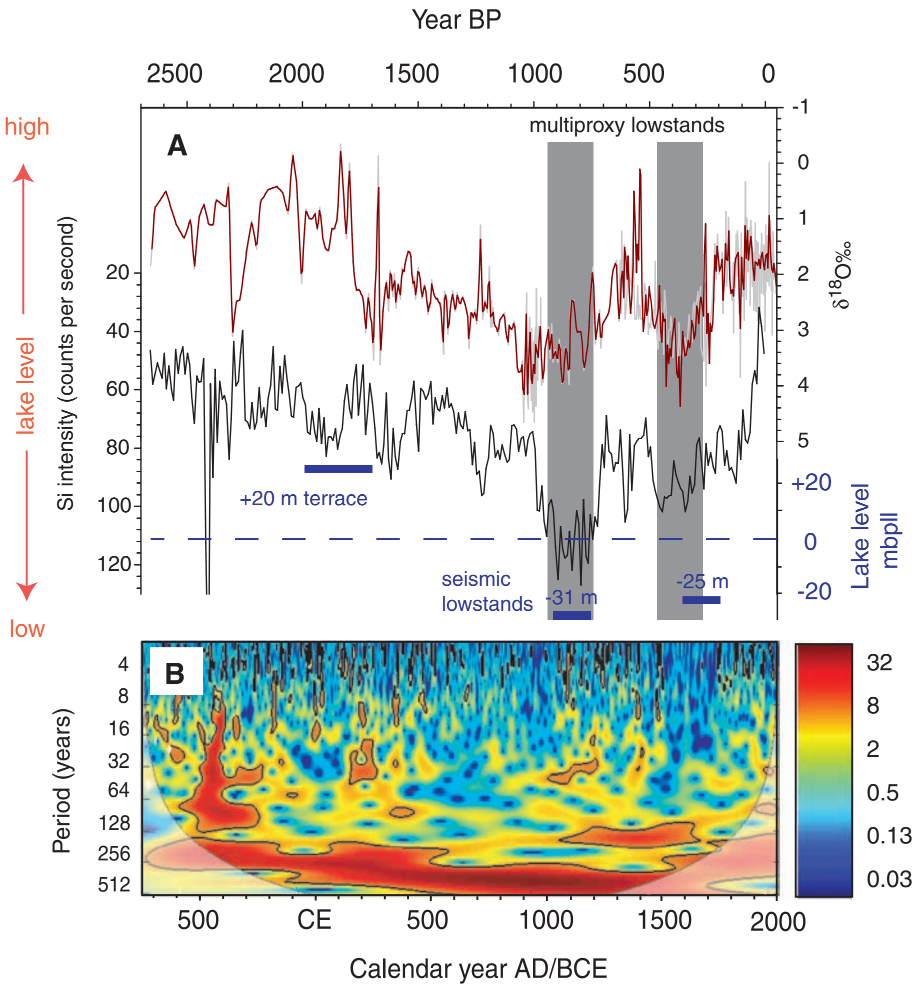

Fig. 2. Paleohydrologic evolution of Lake Bosumtwi. (**A**) Shown are the $\delta^{18}O_{carbonate}$ data (top: red line, 5-year average; gray line, raw data; note the reversed scale), silicon (Si) intensities generated by μ-XRF scanning (middle: black line, note the reversed scale; 10-year averages), and indicators of past lake levels based on emergent terraces and seismic data (bottom: horizontal blue bars). mbpll, meters below present lake level. More positive isotopic values occur during lowstands, which is consistent with a more evaporated lake system. Higher elemental (Si, Al, K, and Ti) concentrations indicate increased transport of terrigenous material to the basin during lowstands, when the base level in the catchment is lowered and more catchment area is exposed to erosion. Vertical gray bars indicate the timing of prominent late Holocene lowstands discussed in the text, as identified in the multiproxy data. (**B**) Evolutive wavelet power spectrum (*28*) computed with a Morlet wavelet (eight octaves, four suboctaves per octave) on the detrended (600-year, 50% spline) PC1 of the XRF data. The black line indicates 95% significance level. Century-scale variability is strong throughout the past approximately three millennia.

Basin (offshore Venezuela) sediments (*35*), suggesting that they may represent an important mode of Atlantic ITCZ variability. The 10.6- and 13.8-year quasi-periodicities are also similar to the dominant meridional mode of SST variability in the tropical Atlantic (11 to 13 years), which is believed to be linked to wind evaporation feedback effects in the tropical Atlantic (*36*).

The strongest frequency component of the sub–century-scale variability is centered on ~40 years (33 to 42 years), suggesting that long-lasting droughts, like those seen in the instrumental record, are a regular feature of the WAM. Because of the potential for producing anomalous narrow-band peaks from noisy data sets using the MTM approach, we confirmed the significance of this multidecadal mode of variability by SSA (*29*), which also produces a curve with an ~40-year period as its fifth and sixth components, and by wavelet analysis, which shows distinct bands of power at multidecadal time scales (*28*) (Fig. 2B). Previous studies have demonstrated that multidecadal drought in West Africa during the instrumental period is primarily driven by changing Atlantic SST patterns (*3*–*5*), and it has been suggested that these patterns may reflect a natural low-frequency mode (65- to 80-year) of SST variability, termed the Atlantic multidecadal oscillation (AMO) (*37*). The relationship between West African rainfall and the AMO is supported by the strong correlations across West Africa over the instrumental period (Fig. 4C). Although the ~40-year mode apparent in the Bosumtwi record is not identical to the instrumental record of the AMO, it is similar to the dominant mode of variability reported from a longer tree-ring–based reconstruction of the AMO (~42.7 years) (*38*) and suggests that the WAM has varied on multidecadal time scales for at least the past 3000 years. To evaluate possible linkages between the AMO and the WAM, we performed a cross-spectral analysis of the Lake Bosumtwi rainfall and tree-ring AMO (*38*) reconstructions. The results suggest that WAM variability and the AMO are coherent and in phase at this 30- to 40-year period over the full 350 years of overlap (Fig. 4B). However, an examination of the power spectra of these records in the time domain (*28*) suggests that this multidecadal variability ranges between ~30 and 65 years (fig. S5). Evolutive cross-wavelet coherence and phase analysis (*39*) demonstrate that despite this nonstationarity, these records remain in phase and coherent, providing additional support for the hypothesized link between multidecadal Atlantic SST variability and the WAM.

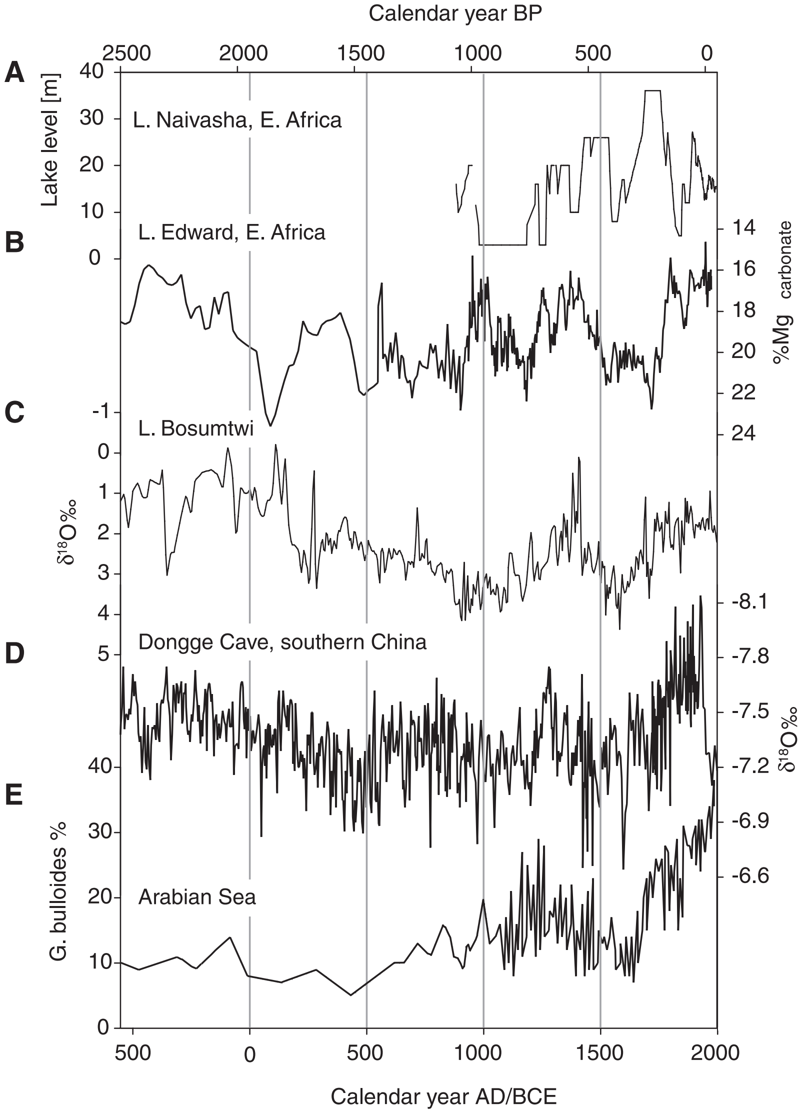

Fig. 3. Records of tropical hydrologic variability. Records are oriented so that a positive water balance is up. (**A**) Lake level variations at Lake Naivasha, East Africa (*19*). (**B**) percent of Mg in carbonate, an indicator of past salinity in Lake Edward, East Africa (*21*). (**C**) δ^{18}O of carbonate from Lake Bosumtwi. (**D**) δ^{18}O of speleothem carbonate from Dongge Cave, southern China (*25*). (**E**) *Globigerina bulloides* abundance in sediment cores from the Arabian Sea, an indicator of monsoon wind strength (*23*, *24*). The records show some differences in their evolution before ~1000 yr B.P. but are remarkably similar over the past few centuries, suggesting that these tropical climate systems are linked. An exception is the Lake Naivasha record, which is out of phase with the other records.

These data indicate that long-lasting episodes of alternating wet and dry conditions have been a feature of the WAM over at least the past three millennia and that these modes of variability are linked to changes in the circulation of the Atlantic. There is abundant evidence from both the modern and archaeological record that these hydrologic changes have been important factors in driving the growth and migration of human populations across West Africa (*40*, *41*). Although the most recent multidecadal drought of the 1970s had widespread ecological, political, and socioeconomic impacts, the Lake Bosumtwi reconstruction suggests that the climate system is capable of much more severe and longer droughts, the most recent of which occurred only 200 to 300 years ago. At that time, the level of Lake Bosumtwi dropped by almost four times as much as it did during the drought of the 1970s (*10*). The century-scale pattern of hydrologic changes over the past three millennia suggests that we will eventually shift back into a period of centennial-scale drought conditions much more severe than seen over the past century. The likelihood of such a regime shift may be enhanced by rising global temperatures, which could perturb the system by inducing a slowdown in the MOC with enhanced freshwater inputs into the North Atlantic (*42*), causing the coupled atmosphere-ocean system to switch into a century-long drought mode. Rapidly expanding populations in sub-Saharan Africa depend heavily on monsoon rainfall for agriculture and power generation and are ill prepared to adapt to such a severe drought if it occurred today. Policymakers should move fast to consider concrete strategies and contingency plans for mitigating such unprecedented droughts, which will undoubtedly be exacerbated by rising surface air temperatures in the future (*43*).

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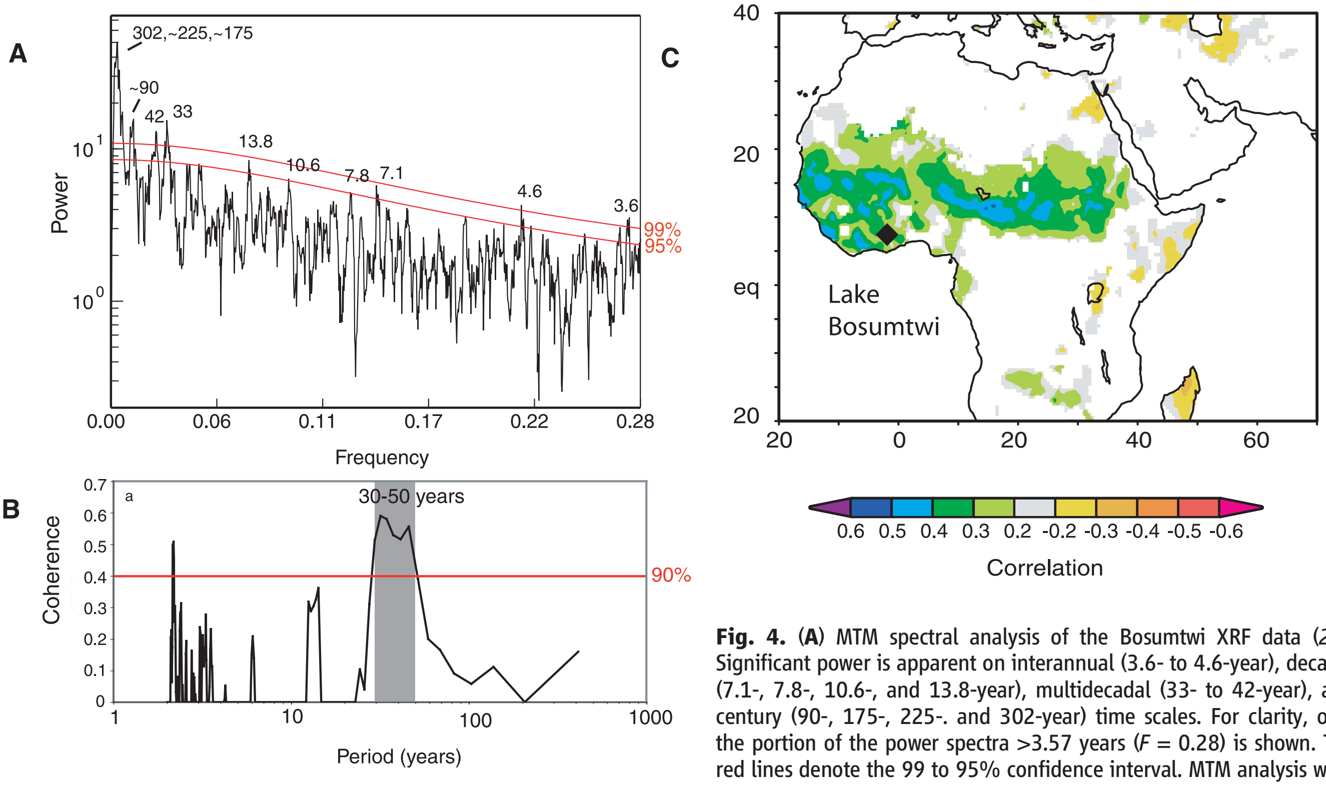

Fig. 4. (**A**) MTM spectral analysis of the Bosumtwi XRF data (*27*). Significant power is apparent on interannual (3.6- to 4.6-year), decadal (7.1-, 7.8-, 10.6-, and 13.8-year), multidecadal (33- to 42-year), and century (90-, 175-, 225-. and 302-year) time scales. For clarity, only the portion of the power spectra >3.57 years (F = 0.28) is shown. The red lines denote the 99 to 95% confidence interval. MTM analysis were performed with the program k-spectra. Parameters p = 3, K = 5, and a null hypothesis of red noise were used in the analysis. Labeled are periods (in years) for peaks that are significant at 95%. (**B**) Cross-spectral coherence computed for Lake Bosumtwi (600-year detrended PC1) and the AMO reconstruction of (*38*). The red horizontal line indicates the 90% confidence interval. The records are in phase and highly coherent at a period of 30 to 50 years (indicated by gray shading). (**C**) Correlations between instrumental records of West African monsoon rainfall (May to October precipitation from the CRU-TS_2.1 data set) (*44*) and the AMO Index [constructed from the HADSST2 dataset (*45*), averaged over the interval from 7° to 75°W and 25° to 60°N for the period 1901–2002], computed with the KMNI Climate Explorer (*46*), suggesting increased precipitation over West Africa (including over Lake Bosumtwi, black diamond) when the AMO is positive (warm anomalies in the North Atlantic).

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