Literature review of mechanisms and timescales involved in the termination of the African Humid Period

James Rees

Writer's Comment: The term paper for my GEL 108 (Paleoclimates) class involved writing about any topic in paleoclimatology or paleo-oceanography. As a geology and history double major, it has always interested me how environmental and climatic dynamics have affected patterns of human settlement, migration, and society. My research focuses on human-environment interactions, a subject that is often overlooked by both historians and planners, and needs to be well understood as our climate continues to change. As a result, I chose to focus on the termination of the African Humid Period, when the Sahara desert changed abruptly from a lush grassland covered by rivers, lakes, vegetation, and human settlements, to the barren, arid, sparsely populated region we know today. I wanted to understand why and how this event unfolded, and how ancient humans were able to respond to such a dramatic shift. Because the literature on the subject is so extensive, I was not able to include the planned anthropology section, and instead focused solely on reviewing the climatology literature.

INSTRUCTOR'S COMMENT: *Close your eyes and try to imagine what north Africa was like at the end of the last ice age. Would you believe from 12,800 to 3,500 BC, the Sahara region was wet, lush and green with a vast river network that flowed into the Atlantic Ocean? Then, over several centuries, the region dried out and became inhospitable as the Sahara Desert expanded. James Rees describes this climatic event and the mechanisms that caused the catastrophic* *drought in Africa in a paper he wrote for the GEL 108 (Paleoclimates). Briefly, the slow wobble of the Earth's axis, which makes a full cycle every 22,000 years, changes the position that Earth's northern hemisphere summer occupies in its elliptical orbit around the sun. When the Earth is closest to the sun (perihelion), the northern hemisphere summer is warmer than when summer occurs at aphelion when Earth is furthest from the sun. The difference in summer warmth causes west African monsoon rainfall to be greatest when the NH summer is at perihelion, thereby producing very wet conditions in north Africa. As the wobble slowly shifts Earth's summers towards aphelion, Earth crosses a climatic tipping point when the monsoon system weakens and north Africa dries out. James describes the cause and effect of these changes on rainfall and vegetation changes in his paper. I congratulate him on a well written paper on this topic.*

—Howard J. Spero, Department of Earth and Planetary Sciences

Introduction

The African Humid Period (AHP) occurred between 14,800 and 5,500 years BP and was characterized by an expansion of the West African monsoon that initiated an increase in precipitation across North Africa (Shanahan et al., 2015). The onset and termination of the AHP coincides with fluctuations in incident radiation at northern latitudes due to the Earth's eccentricity and precessional cycles (DeMenocal et al., 2000). From roughly 6 ka–5 ka BP, decreasing solar insolation at the northern mid- to low latitudes decreased monsoonal energy. This led to a southward migration of the African monsoonal rain belt over the mid- to late Holocene, which was enhanced by climate feedbacks including dust, vegetation, and albedo (Collins et al., 2017). Initial proxies for precipitation levels at the terminus of the AHP include fluctuations in pluvial lakes such as Lake Mega-Chad and Bosumtwi, in addition to aeolian dust composition derived from offshore sediment cores (Armitage et al., 2015, Street and Grove, 1978, Shanahan et al., 2015, DeMenocal et al., 2000). More recent studies have looked at hydrogen isotope composition of leaf waxes (Armitage et al., 2015, Shanahan et al., 2015). While the vast majority of research on the end of the AHP has indicated aridification occurred rapidly (on the scale of decades/centuries) in a roughly 1 millennia window from 6 ka–5 ka BP, more recent studies suggest the retreat lasted from about 7,000 years BP to around 2,500 years BP (Shanahan et. al., 2015). This paper aims to review the available precipitation proxies for North Africa at the termination of the AHP to evaluate the mechanisms and timescales in which the termination occurred. This will help aid our understanding of how human civilizations adapted to this changing environment.

Proxies and evidence for precipitation changes at the end of AHP

The earliest proxies studied for the end of the AHP were fluctuations in large pluvial lake levels determined from radiocarbon dating of sediments and fossils in lake beds. These early studies were synthesized in a review paper by Street and Grove (1978), who concluded that pluvial lakes in North Africa experienced desiccation from approximately 6 ka BP to 5 ka BP.

At the peak of the AHP approximately 10,000 years BP, paleolake Mega-Chad was the largest freshwater lake in Africa and perhaps the largest pluvial lake on Earth (Armitage et al., 2015). Armitage et al. (2015) developed a chronology of lake levels using sedimentary structures and fossils preserved in the beds underlying Lake Mega-Chad. Radiogenic dating of shell fragments reveal lake levels to be at a highstand of 329 meters at roughly 5 ka BP, when both the Bodélé Depression and Lake Chad were a single body of water, Lake Mega-Chad (Fig. 1) (Armitage et al., 2015). Reactivation of dunes at Erg du Djourab began at 4.7 ka +/- 0.2 ka BP, which demonstrates lake levels in the Bodélé Basin to be no higher than 224 meters, and levels at Lake Chad to be no higher than 288 meters, at which point it stops feeding the Bodélé Basin (Mauz and Felix-Henningsen, 2005). This translates to a roughly 100-meter drop in lake level in the Bodélé Basin and a 40-meter drop in the level of Lake Chad at a centennial scale (100-500 years). The desiccation of Lake Mega-Chad stands as evidence of a significant centennial scale decrease in lakeshore level in the Sahara.

At lower latitudes, Shanahan et al. (2015) performed radiocarbon dating of highstand terraces and lacustrine silts around Lake Bosumtwi, indicating the lake was roughly 110 meters above its current level until

5.7 ka BP, and had receded to near modern levels around 2.8-3.5 ka BP, revealing that an onset of aridification occurred slightly later than Lake Mega-Chad to its north. These initial studies all supported the hypothesis that aridification occurred rapidly, over decades or centuries, just as the onset of the AHP had occurred at 14 ka BP.

Radiocarbon dating of sediment cores supports the hypothesized rapid termination of the AHP at about 5.4 ka BP that had been established by studies of pluvial lake-level fluctuations. DeMenocal et al. (2000) drilled sediment cores from the eastern equatorial Atlantic. During the boreal winter months, regional atmospheric circulation is dominated by NE trade winds, which advects and transports an estimated 400x106 tons of mineral aerosol dust annually from the Sahara and Sahel in Northwest Africa to the eastern subtropical Atlantic (DeMenocal et al., 2000). Examination of dust composition from cores revealed a steep drop in biogenic carbon and a sharp increase in terrigenous sediment at 5.5-5.4 ka BP (Fig. 2) (DeMenocal et al., 2000). These changes demonstrate the rapid (decadal or centennial scale) onset of arid conditions in northern Africa in general, supporting rapid aridification inferred from pluvial lake levels.

Shanahan et al. (2015) solvent extracted lake sediments from Lake Bosumtwi. They isolated saturated hydrocarbons from leaf waxes and performed a stable isotope analysis of individual n-alkanes (Shanahan et al., 2015). Isotope values were measured against calibrated gas and reported in Vienna Standard Mean Ocean Water (VSMOW) (Shanahan et al., 2015). Final δDwax was corrected for ice volume and vegetation discrimination (Shanahan et al., 2015). Using this reconstructed δDwax record, Shanahan et al. (2015) found that precipitation in the Lake Bosumtwi catchment slowly decreased from around 10 ka BP to 5.4 ka BP and then rapidly decreased from approximately 5.4–4.2 ka BP (Fig. 3). This rapid timescale agrees with δDwax records from the Gulf of Guinea, which also record a rapid aridification between 5.8 and 4.8 ka BP (Collins et al., 2017).

While Shanahan's (2015) paper only performed a single isotope analysis, it also synthesized all available published proxies of North African precipitation to discover a more complex, time-transgressive onset of arid conditions in the Sahara and Sahel. Their findings indicated that the sudden aridification observed in previous studies was a mischaracterization resulting from observing changes only at a local scale. For example, the coast of Senegal (15 degrees north) saw a rapid onset of aridification at 7.1 ka BP, while the Congo Fan, closer to the equator, saw a decrease in precipitation occur at 2.9 ka BP (Shanahan et al., 2015). According to their study, while aridification occurred rapidly on a local scale, the termination of the AHP occurred over a longer period (approximately 8 ka to 3 ka BP) with arid conditions commencing in higher latitudes first and gradual moving south (Fig. 4) (Shanahan et al., 2015). This contradicts the vast majority of previous studies that claim a rapid termination of the AHP occurred from roughly 6 ka–5 ka BP.

Mechanisms involved in the termination of the AHP

A strengthened West African Monsoon caused by increased northern hemisphere solar insolation has been the most widely accepted mechanism for the AHP. Jalihal et al. (2019) used a fully coupled ocean-atmosphere GCM to model 100-year climate simulations at two precessional extremes: 1) $P_{min,}$ where the NH summer solstice is at perihelion, and $P_{max,}$ where the NH winter solstice is at perihelion. This leads to a stronger seasonal cycle in the Northern Hemisphere and Southern Hemisphere, respectively (Jalihal et al., 2019). The model predicted a nearly 100 W m^{-2} difference in solar incident radiation between P_{min} and P_{max} at northern tropical latitudes (between 0 and 30 degrees) during summer months (Fig. 5) (Jalihal et al., 2019). The study demonstrated how the Earth's precession can effect summer solar insolation at tropical northern latitudes, and calculated that the 100 W m^{-2} increase in summer solar insolation translates to an average increase of 10 mm day^{-1} of precipitation from the West African Monsoon (Jalihal et al, 2019).

Earlier studies, such as Prell and Kutzbach (1987), used GCM's to understand how exactly increased NH summer insolation resulted in increased rainfall over North Africa. They modeled precipitation responses to northern latitude insolation over the last 150,000 years (Prell and Kutzbach, 1987). They found that increased solar radiation heated land surface more than ocean surface waters, producing a larger land-ocean pressure gradient, which strengthened monsoonal winds and their penetration into Africa's interior (Prell and Kutzbach, 1987).

Kutzbach and Liu (1997) developed similar climate models to test the effects of increased solar insolation on sea surface temperature

(SST). They found that: 1) over the entire tropical Atlantic, the increased insolation associated with late-summer perihelion increased the solar radiation absorbed by the surface ocean, and 2) over the northern tropical Atlantic, evaporative heat loss from the ocean was reduced (Kutzbach and Liu, 1997). This offers a mechanism for an overall increase in evaporation which, when transported by the strengthened monsoonal winds described in Prell and Kutzbach (1987), provides a mechanism for the increased moisture transport further into North Africa's interior, thereby explaining the increase in precipitation across the Sahara and Sahel during the AHP.

When considering only the linear relationship between insolation forcing and monsoonal strength, the termination of the AHP would appear to be a result of precession drawing the NH summer solstice away from perihelion, which reduced NH summer solar insolation—lowering the land-ocean temperature gradient off the Atlantic coast of North Africa—and lowered the volume of water vapor that could be transported by the weakened West African Monsoon. This hypothesis supports a time-transgressive aridification of North Africa consistent with the timescale established in Shanahan et al. (2015) and compatible with the findings of DeMenocal et al. (2000), who demonstrated the onset and termination of the AHP to occur when summer solar insolation reached an identical threshold value of 4.2% greater than present. Thus, the timing of precession cycles and resulting reduction in solar insolation at 6-5 ka BP aligns with the precipitation proxies observed across North Africa.

However, DeMenocal et al. (2000) observed that the modeled increases and subsequent decreases in precipitation from fluctuations in the West African monsoon and SST were not great enough to account for the observed changes in precipitation calculated from proxies. Additionally, the linear model of isolation forcing is compatible with a time-transgressive aridification of the Sahara and Sahel (Fig. 6, Graph B), but does not explain the rapid termination that is evident in most of the proxies. It is only when fluctuations in solar insolation are coupled with land surface vegetation and dust feedbacks that North Africa becomes sufficiently humid year round to support large perennial lakes (Fig. 6, Graphs C and D) (DeMenocal et al., 2000). The locally abrupt aridification of North Africa observed in many samples is not compatible with the time-transgressive model proposed by Shanahan et al. (2015), and thus soil-moisture and vegetation feedbacks may have played a role to make local scale change more abrupt.

Drought-induced vegetation decreases served as one of the positive feedbacks during the termination of the AHP. Rachmayani et al. (2015) used GCM's to model precipitation anomalies during the early and mid-Holocene in North Africa. Using a coupled climate climate-vegetation model, they found that when dynamic vegetation was included in the model, it resulted in an approximately 20% greater precipitation anomaly in the Sahara-Sahel region during the mid to late-Holocene when compared to fixed vegetation models (Rachmayani et al., 2015). The study concluded that when monsoonal precipitation moved northward during the early Holocene, vegetation expanded (Rachmayani et al., 2015). This enhanced latent surface cooling through canopy evapotranspiration, which in turn decelerated the African easterly jet (AEJ), a phenomenon that is associated with positive Saharan and Sahelian rainfall anomalies (Rachmayani et al., 2015). A decrease in monsoonal rainfall would produce the opposite effect, accelerating the AEJ and further decreasing precipitation, which is assumed to have occurred at the termination of the AHP (Collins et al, 2017). However, the study conceded that even with dynamic vegetation feedbacks enabled, their GCM still underestimated early to mid-Holocene monsoonal rainfall in the Sahara and Sahel by a factor of 2 (Rachmayani et al., 2015). This implies that vegetation feedbacks, while potentially a factor, cannot accompany monsoonal changes and decreased SST's as the sole feedback mechanism contributing to the termination of the AHP.

A closer agreement with proxy records is achieved only when dust concentrations are included as a feedback alongside vegetation in a single climate model (Pausata et al., 2016). The study used GCM's to model the effect of dust and vegetation on precipitation in North Africa at 6 ka BP (Pausata et al., 2016). The study looked at 6 different scenarios of dust/vegetation conditions and found that a combination of shrub vegetation cover and reduced dust resulted in the strongest/wettest West African Monsoon (Pausata et al., 2016). The researchers hypothesized this is due to the decreased albedo caused by vegetation and soil replacing sand as the dominant land cover, along with the reduction in high-albedo dust particles. Reduced albedo results in more shortwave radiation reaching the surface, which is subsequently heated just prior to monsoon season, driving an intensification of the monsoon itself (Pausata et al., 2016).

Again, a weakened monsoon at the end of the AHP would produce the opposite effect, and along with vegetation feedbacks would result in rapid aridification that matches proxy records.

Conclusions

Thus, while the decreased summer solar insolation was the trigger for the termination of the AHP, considering only the changes in monsoonal temperature and SST as mechanisms would necessitate a gradual aridification everywhere and fail to increase rainfall to levels observed in proxies. Instead, rapid aridification on the decadal and centennial scales occurred at most sampled locations. Shanahan et al. (2015) reconciles this discrepancy by suggesting overall precipitation decreased gradually across the continent, with dust and vegetation feedbacks similar to those explained in DeMenocal et al. (2000) leading to rapid aridification at local scales. Collins et al. (2017) proposed that the time-transgressive timescale is flawed, as the synthesis (Fig. 4) is based on discontinuous records, many of which are not as accurate and are based on different hydrologic indicators. Ultimately, while precessional cycles and accompanying feedbacks have been confirmed as the initial trigger of the AHP termination, the timescale at which the termination occurred and the degree to which feedbacks affected precipitation remains a topic of debate.

References

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

Collins, J.A., Prange, M., Caley, T., Gimeno, L., Beckmann, B., Mulitza, S., Skonieczny, C., Roche, D., Schefuss, E., 2017. Rapid termination of the African Humid Period triggered by northern high-latitude cooling. Nat. Commun. 8, 1372.

DeMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinsky, M., 2000. Abrupt onset and termination of the African Humid Period:: rapid climate responses to gradual insolation forcing. Quaternary Science Reviews 19, 347–361.

Jalihal, C., Bosmans, J.H.C., Srinivasan, J., Chakraborty, A., 2019. The response of tropical precipitation to Earth's precession: the role of energy fluxes and vertical stability. Clim. Past. 15, 449–462.

Kutzbach, J.E., Liu, Z., 1997. Response of the African Monsoon to Orbital Forcing and Ocean Feedbacks in the Middle Holocene. Science 278, 440–443.

Mauz, B., Felix-Henningsen, P., 2005. Palaeosols in Saharan and sahelian dunes of Chad: archives of Holocene North African climate changes. Holocene 15, 453–458.

Pausata, F.S.R., Messori, G., Zhang, Q., 2016. Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period. Earth Planet. Sci. Lett. 434, 298–307.

Prell, W., Kutzbach, J., 1987. Monsoon Variability Over the Past 150,000 Years. J. Geophys. Res.-Atmos. 92, 8411–8425.

Rachmayani, R., Prange, M., Schulz, M., 2015. North African vegetation-precipitation feedback in early and mid-Holocene climate simulations with CCSM3-DGVM. Clim. Past. 11, 175–185.

Shanahan, T.M., McKay, N.P., Hughen, K.A., Overpeck, J.T., Otto-Bliesner, B., Heil, C.W., King, J., Scholz, C.A., Peck, J., 2015. The time-transgressive termination of the African Humid Period. Nat. Geosci. 8, 140–144.

Street, F.A., Grove, A.T., 1979. Global maps of lake-level fluctuations since 30,000 years BO. Quaternary Research 12, 83-118.

Appendix

Figure 1. Map showing fluctuations in lake level of Lake Mega-Chad (from Armitage et al., 2015). When lake level drops below 288 m, the Bahr el Ghazal outlet is cut off and Lake Chad stops feeding the Bodélé Depression.

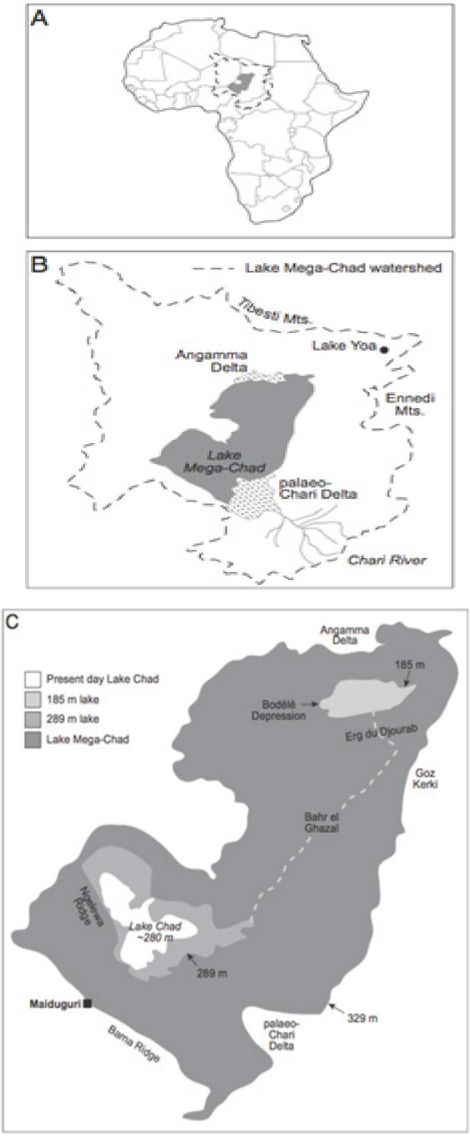

Figure 2. Graph showing spike in terrigenous sediment deposition from 6-5 ka BP that coincides with decreased solar incident radiation at 20 degrees north (from De-Menocal et al., 2000). The increase in terrigenous sediment deposition is interpreted to be a result of increased dust advection from aridification.

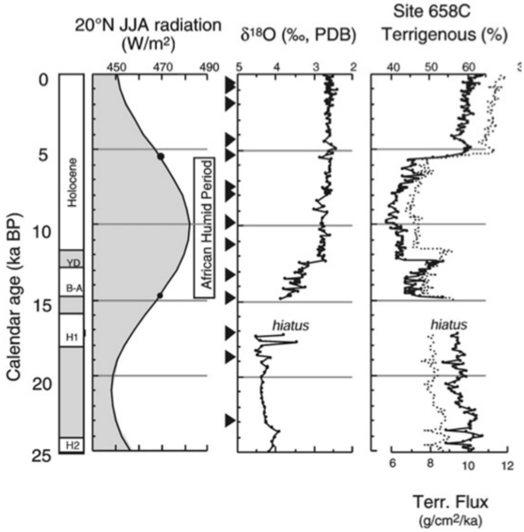

Figure 3. δD_{wax} percentages as a proxy for precipitation (from Shanahan et al., 2015).

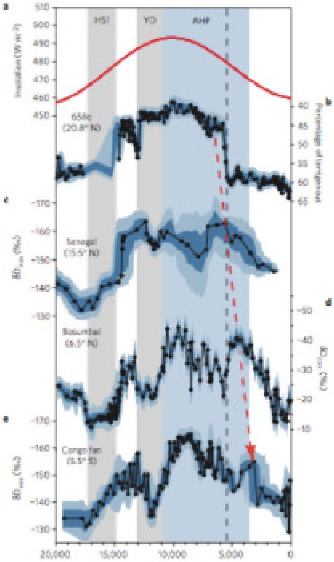

Figure 4. Synthesis of proxies for the end of the AHP (from Shanahan et al., 2017). Shanahan noticed a clear north to south trend in the onset of aridification that is contrary to the well-established hypothesis rapid termination.

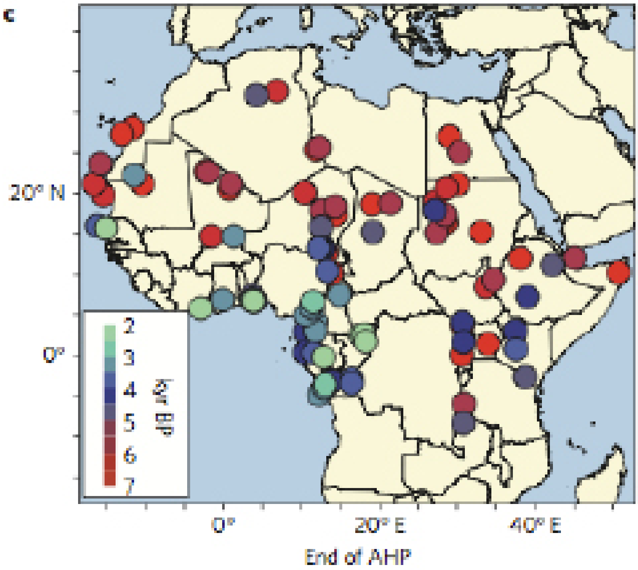

Figure 5. The difference in the incoming solar radiation at the top of atmosphere between P_{min} *and* P_{max} *as a function of latitude and month (from Jalihal et al., 2019).*

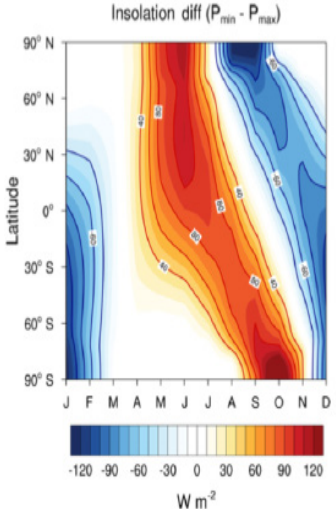

Figure 6. Model predictions from GCM's showing a) summer solar insolation; b) precipitation response to radiation forcing; c) vegetation cover response to radiation forcing; and d) terrigenous sediment deposition in eastern equatorial Atlantic in response to radiation forcing (from DeMenocal et al., 2000).