BASIC

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Green Sahara: African Humid Periods Paced by Earth's Orbital Changes

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Citation: deMenocal, P. B. & Tierney, J. E. (2012) Green Sahara: African Humid Periods Paced by Earth's Orbital Changes. *Nature Education Knowledge* 3(10):12

Paleoclimate and archaeological evidence tells us that, 11,000-5,000 years ago, the Earth's slow orbital 'wobble' transformed today's Sahara desert to a land covered with vegetation and lakes.

As he crossed by caravan from Tripoli to Timbuktu in the mid 1800s, the German explorer Heinrich Barth became the first European to discover the then-mysterious prehistoric Saharan rock paintings and engravings, which we now know date back to the African Humid Period, a humid phase across North Africa which peaked between 9,000 and 6,000 years ago. These masterfully-rendered images depict pastoral scenes with abundant elephants, giraffe, hippos, aurochs (a wild ancestor of domestic cattle), and antelope, occasionally being pursued by bands of hunters (Figure 1). The Sahara is very likely the world's largest art museum with hundreds of thousands of elaborate engravings and paintings adorning rocky caves and outcrops. The incongruence of these lively images in such lifeless settings intrigued Barth, who noted that the art work "bears testimony to a state of life very different from that which we are accustomed to see now in these regions" (Barth, 1857).

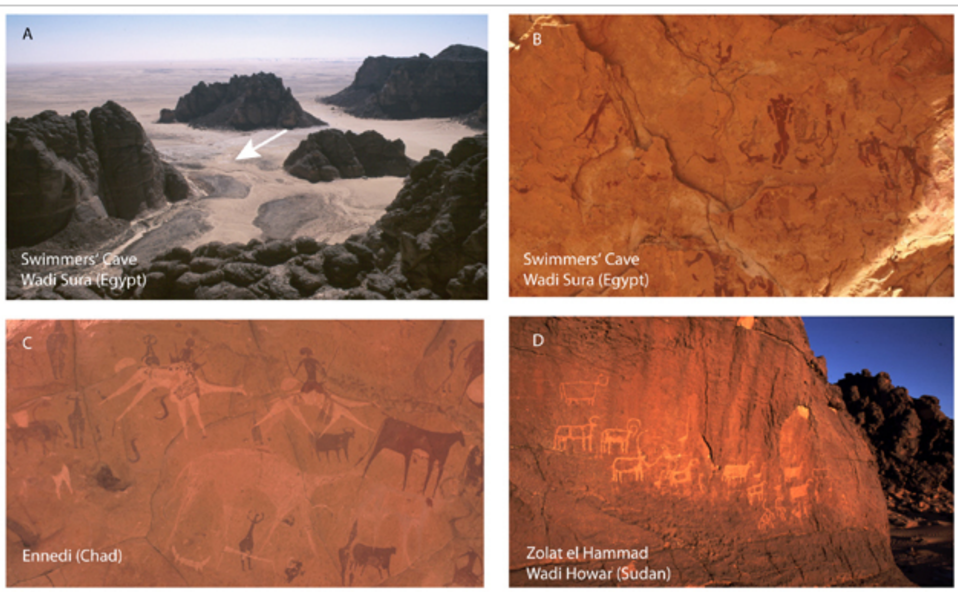

Figure 1: Images of North African prehistoric rock and cave paintings.

From (a, b) Swimmer's Cave (Wadi Sura, southern Egypt), (c) the Ennedi massif (northeastern Chad) and (d) Zolat el Hammad, Wadi Howar (northern Sudan).

We now know that these images document a dramatic climate change across North Africa from the hyperarid desert it is today to a nearly completely vegetated landscape dotted with large and small lakes during the early and middle Holocene epoch. This event is commonly called the "African Humid Period (AHP)". The AHP was a direct result of African monsoonal climate responses to periodic variations in the Earth's orbit around the Sun that recur roughly every 20,000 years. Impressively, the AHP is just the most recent of hundreds of earlier humid events spanning as far back as the Miocene (9 million years ago) and likely much earlier.

Orbital Forcing of Subtropical Climate

The Earth's axial rotation is perturbed by gravitational interactions with the moon and the more massive planets that together induce periodic changes in the Earth's orbit, including a 100,000 year cycle in the shape of the orbit (eccentricity), a 41,000 year cycle in the tilt of the Earth's axis (obliquity) and a 20,000-year cycle in the "wobble" — much like a top wobbles — of the Earth's axis (precession). All three of orbital cycles — called Milankovitch cycles — impact African climate on long geologic timescales, but the cycle with the most influence on the rains in Africa is the "wobble" cycle, precession. The main climatic effect of precession is to shift the season when the Earth has its closest pass to the Sun (perihelion) — the so-called precession of the equinoxes. Today, perihelion occurs in northern hemisphere winter but at 10,000 years ago (half of a precession cycle) it occurred in northern hemisphere summer, and summer radiation over North Africa was about 7% higher than it is today (Berger, 1988; Kutzbach, 1981) (Figure 2a).

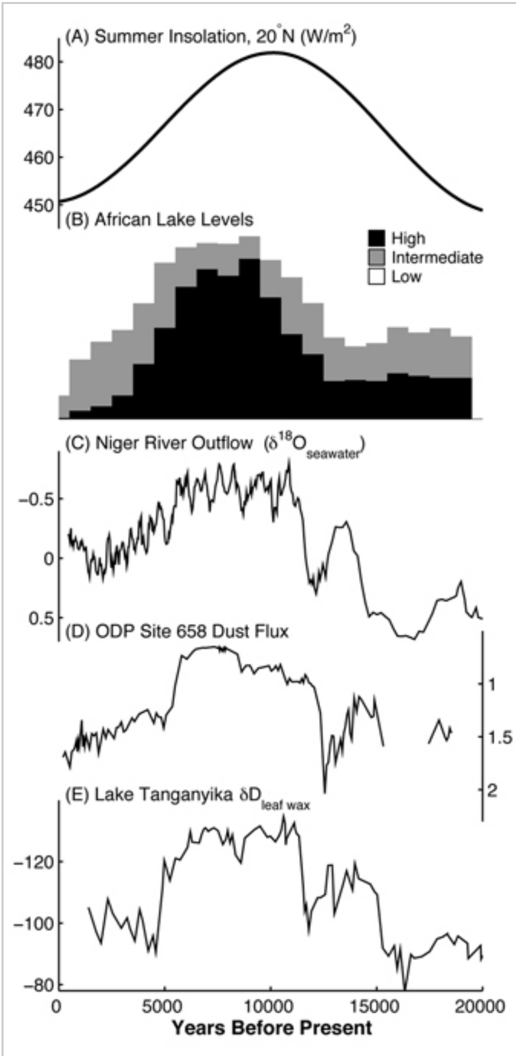

Figure 2

(a) Change in seasonal (summer) insolation for North Africa (20˚N) and paleoclimate records of the African Humid Period: (b) African lake level status (updated Oxford Lake Level Database; COHMAP members, 1988, Street-Perrott ***et al.***, 1989, Tierney ***et al.***, 2011), (c) Niger River outflow inferred from $\delta^{18}O_{seawater}$, (Weldeab ***et al.***, 2005); (d)

Ocean Drilling Program (ODP) Site 658 dust flux (deMenocal ***et al.***, 2000, Adkins ***et al.***, 2006); (e) Lake Tanganyika δD of leaf waxes (δD_{wax}; Tierney ***et al.***, 2008).

Orbital precession greatly influences North African climate because it controls the strength and northward penetration of the monsoonal rains (Kutzbach, 1981; Liu *et al.*, 2006). Strengthening summer-season solar radiation causes the North African landmass to heat up relative to the adjacent Atlantic Ocean due the lower thermal inertia of the land surface relative to the upper ocean mixed layer. The warmer land mass creates a broad low pressure zone, driving the inflow of moist air from the tropical Atlantic. The resulting summer monsoonal rains nourish the landscape. During winter, the land cools relative to the ocean and the winds reverse (one definition of a monsoon), returning dry conditions across North Africa. Since precession controls summer insolation, it effectively controls the amount and northward penetration of the monsoonal rains into North Africa. Simple atmosphere-only climate models have shown that a 7% increase in summer radiation, similar to what occurred during the AHP, results in at least a 17% increase in African monsoonal rainfall, and up to 50% if ocean feedbacks are included (Kutzbach and Liu, 1997).

Evidence for the African Humid Period

The Early Holocene AHP is one of the most thoroughly documented and well-dated climate change events in the geologic record, and the number and diversity of paleoclimate records is remarkable (COHMAP Members, 1988; deMenocal *et al.*, 2000; Gasse, 2000; Hoelzmann *et al.*, 1998; Jolly, 1998; Kroepelin, 2008; Kuper and Kröpelin, 2006). Through these terrestrial and marine records we can document both the timing and extent of the humid interval.

Geological evidence for past lake basins in the Sahara are commonly found near interdune depressions and other low-lying regions, where ancient lake bed sediment outcrops and shoreline deposits are exposed. Most of the early Holocene paleolakes were small, but numerous and widespread (Figure 2b). Some lake basins in North Africa were exceptionally large, as large as the Caspian Sea today. These so-called megalakes occurred in the North (Megalake Fezzan, Libya), South (Megalake Chad, Chad/Niger/Nigeria), West (Chotts Megalakes, Algeria) and East (Megalakes Turkana and Kenya) (Drake and Bristow, 2006). Based on their stratigraphic records, these must have been permanent, open-basin lakes, indicating that annual moisture supply exceeded evaporation for many millennia during the AHP, even in the driest regions of the modern-day Sahara.

A continent-wide compilation of past lake-level reconstructions (the Oxford Lake Level Database (OLLD) (COHMAP Members, 1988; Street-Perrott *et al.*, 1989)) updated with lake-level reconstructions published in the last twenty years (Tierney *et al.*, 2011) chronicles the changes in lake levels that occurred across Africa as a result of the African Humid Period (Figure 2b). This database classifies lakes as "low" (lake is within 0-15% of its potential volume or dry), "intermediate" (lake is within 15-70% of its potential volume) or "high" (lake is within 70-100% of its potential volume or overflowing) every 1000 years during the late-glacial period and the Holocene. The difference in lake levels at 9000 years — the height of the African Humid Period — relative to the conditions today shows that the extent of the AHP across the continent was vast — extending from the far northern Sahara to as far south as 10˚S in East Africa (Figure 3).

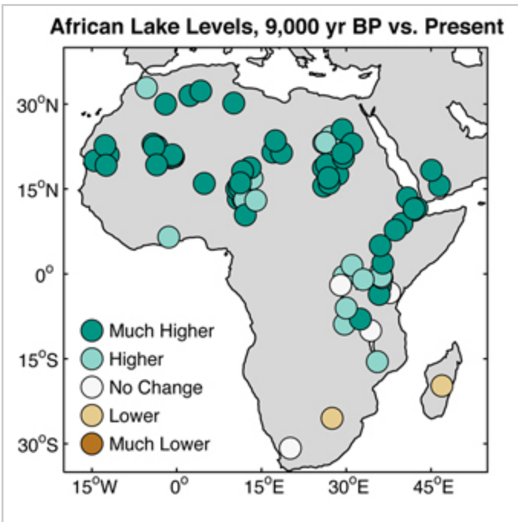

Figure 3: Distribution map of reconstructed lake levels across Africa, 9,000 years ago relative to today.
Data are from the Oxford Lake Level Database (COHMAP members, 1988, Street-Perrott ***et al.***, 1989) updated with lake-level reconstructions generated in the last twenty years (Tierney ***et al.***, 2011).

The Nile River drainage basin is the largest of North Africa, draining runoff from the eastern Sahara, Ethiopian highlands and equatorial East Africa into the Eastern Mediterranean. Today, the largest contributor is the Blue Nile tributary which drains summer monsoonal runoff from the Ethiopian highlands. During the African Humid Period, enhanced Nile River runoff flooded into the eastern Mediterranean Sea where the resulting freshwater cap led to anoxic conditions and deposition of organic-rich sapropel deposits on the seafloor. Radiocarbon dates of these sapropel deposits constrain peak Nile River runoff to between 11,000 and 6,000 years ago (Mercone *et al.*, 2000; Rohling, 1994). Longer stratigraphic sections extending as far back as the Miocene (Hilgen *et al.*, 1995) contain hundreds of these sapropel layers, each representative of an earlier African humid phase and each paced by the characteristic orbital precession beat of 20,000 years (Figure 4). These sapropel layers are packaged into groups of 4-5 (Figure 4), reflecting the influence of slight changes in the shape of the Earth's orbit around the sun (eccentricity) on modulating the strength of the precessional beat.

Figure 4: Photograph of late Miocene (9.3-8.4 Ma) sapropel bedding cycles from the Gibliscemi exposure in south central Sicily (Hilgen *et al.*, 1995; Krijgsman *et al.*, 1995).
The darker strata are organic-rich sapropel layers that were deposited during African humid periods when enhanced monsoonal rainfall and Nile River runoff led to increased Mediterranean stratification and reduced ventilation of its deep eastern basin. The sapropels occur every 20,000 years but are bundled into groups of 4-5, reflecting the additional influence of orbital eccentricity. Photograph courtesy of Frits Hilgen and the Utrecht research group on astronomical climate forcing and timescales.

The next largest drainage basin of North Africa is the Niger River, whose inland catchment includes much of northwest and north-central Africa. A record of past changes in the outflow of the Niger River to the equatorial Atlantic Ocean has been reconstructed using measurements of the magnesium/calcium (Mg/Ca) and oxygen isotope (d ^{18}O) ratios in fossil planktonic foraminifera in an ocean sediment core taken near the Niger River delta region (Weldeab *et al.*, 2005). Microscopic foraminifera shells are preserved in ocean sediments and geochemical analyses of these shells can be used to estimate the tropical Atlantic d$^{18}O_{seawater}$, a reliable proxy for the ocean's salinity where the fresh Niger River runoff mixes with the salty water of the open ocean. In this record, shown in Figure 2c, the African Humid Period can be readily identified as the period of low salinity (low d$^{18}O_{seawater}$) between 11,500-5,000 years ago (Weldeab *et al.*, 2005).

Another independent proxy of North African rainfall is the abundance of wind-blown dust preserved in deep-sea sediments off the Northwest African coast. Today, North Africa is one of the largest exporters of atmospheric mineral dust due to its extreme rainfall seasonality, loose soils, and strong transporting winds. Site 658 is a sediment core taken off the coast of Mauritania (near 20°N) through the Ocean Drilling Program (ODP) and has a high rate of sediment accumulation due to the large fluxes of mineral dust and marine microfossils to the seafloor (deMenocal *et al.*, 2000). The supply of terrigenous sediment here is dominated by this dust, and the down-core record of dust flux shows that the AHP can be clearly recognized an interval of low dust fluxes between 11,500 and 5,500 years ago (Figure 2d) (Adkins *et al.*, 2006). A surprising discovery from this high-resolution record was that the onset and termination of the AHP appeared very abrupt, occurring within one to two centuries. The record also resolves the sharp increase in dust and aridity during the Younger Dryas cool period (12,700-11,500 years ago), also apparent in the Niger River outflow record as an interval of reduced flow (higher salinity) at this time (Figure 2c).

As the distribution of past lake-level data indicate (Figure 3), most of East Africa experienced humid conditions at the same time as North Africa. A hydroclimatic record from Lake Tanganyika — the second deepest lake in the world — based on the hydrogen isotopic composition of fossil leaf waxes (dD_{wax}) highlights the major features of the African Humid Period in East Africa (Tierney *et al.*, 2008) (Figure 2e). Leaf waxes are ablated from vegetation surrounding the lake and transported by wind and water to the sediments, where they are well-preserved. The dD value of the leaf waxes is a proxy for relative aridity: plants record lower dD_{wax} values when the climate is humid, and higher dD_{wax} values when it is dry. As in the records of Niger River outflow and Sahara dust flux, the African Humid Period is easily identified in the dD_{wax} record from Lake Tanganyika as the very low dD_{wax} values that occur between 11,500 and 5,000 years ago. These low values indicate rainy conditions as well as a potentially greater contribution of rain from the Atlantic (Tierney *et al.*, 2008; Tierney *et al.*, 2011). Like the Sahara dust flux record, the initiation and termination of the humid period at Lake Tanganyika appears to have been abrupt, occurring within a few centuries.

On the Timing and Abruptness of the African Humid Period Transitions

Although the African paleoclimate records shown in Figures 2 and 3 document a continental-wide pervasiveness of the African Humid Period, the transitions into and out of the AHP may not have been synchronous across all of North Africa (Hoelzmann *et al.*, 2002; Kuper and Kröpelin, 2006), nor were they likely uniformly abrupt (e.g. Figure 3d and e) everywhere. For example, a pollen record of paleovegetation change in the eastern Sahara, extracted from a sediment core from Lake Yoa in northern Chad, documents a gradual end of humid conditions between 5-3 ka BP (Kröpelin *et al.*, 2008). Also, transects of paleohydrological and paleoecological data from the eastern Sahara indicate that the transition out of the humid period was time-transgressive, with dry conditions established earlier in the north (Egypt) and later in the south (Sudan and East Africa; Hoelzmann *et al.*, 2002; Kuper and Kröpelin, 2006).

One abrupt event that appears to be synchronous across much of North and East Africa is the occurrence of dry conditions during the Younger Dryas period (12,700-11,500 years ago), when cool conditions prevailed over much of the northern hemisphere and particularly over the North Atlantic Ocean (Figure 2b-e; (Gasse, 2000; Broecker, 2003; deMenocal *et al.*, 2000; Schefuß *et al.*, 2005; Tierney *et al.*, 2008; Tjallinghi *et al.*, 2008; Weldeab *et al.*, 2005)). Climate models have confirmed that reduced North Atlantic temperatures weaken African monsoonal circulation and reduce regional rainfall (Tjallingii *et al.*, 2008).

One of the most fascinating aspects of the African Humid Period is its impact on North African human sustainability and cultural development (Hoelzmann *et al.*, 2002; Kuper and Kröpelin, 2006). North Africa was nearly completely vegetated during the height of the AHP (Jolly *et al.*, 1998) and populated with nomadic hunter-gatherer communities that increasingly practiced pastoralism (husbandry of cattle, sheep, and goats; Hoelzmann *et al.*, 2002; Kuper and Kröpelin, 2006). The rock art images in Figure 1 depict impressions of this life. Towards the end of the African Humid Period between 7,000 and 5,000 years ago the progressive desiccation of the region led to a widespread depopulation and abandonment of North African sites. These populations did not disappear, however. The large-scale exodus was coincident with the rise of sedentary life and pharaonic culture along the Nile River (a perennial water source) and the spread of pastoralism throughout the continent (Kuper and Kröpelin, 2006).

Summary

The African Humid Period exemplifies the dramatic climate transitions that our planet experiences as a result of subtle changes in the Earth's orbit. The "greening" of the Sahara not only represents a remarkable transformation of the hydrologic cycle, but evidence that gradual climate forcing can result in rapid climate responses. The wealth of North African paleoclimate and archeological data highlights the fundamental importance of water availability on sustainability and human populations, and the central role of climate in shaping major events in cultural development leading to the rise of complex, urban cultures (deMenocal, 2001; Kuper and Kröpelin, 2006).

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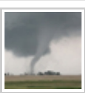

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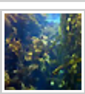

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