Milankovitch Cycles, Paleoclimatic Change, and Hominin Evolution

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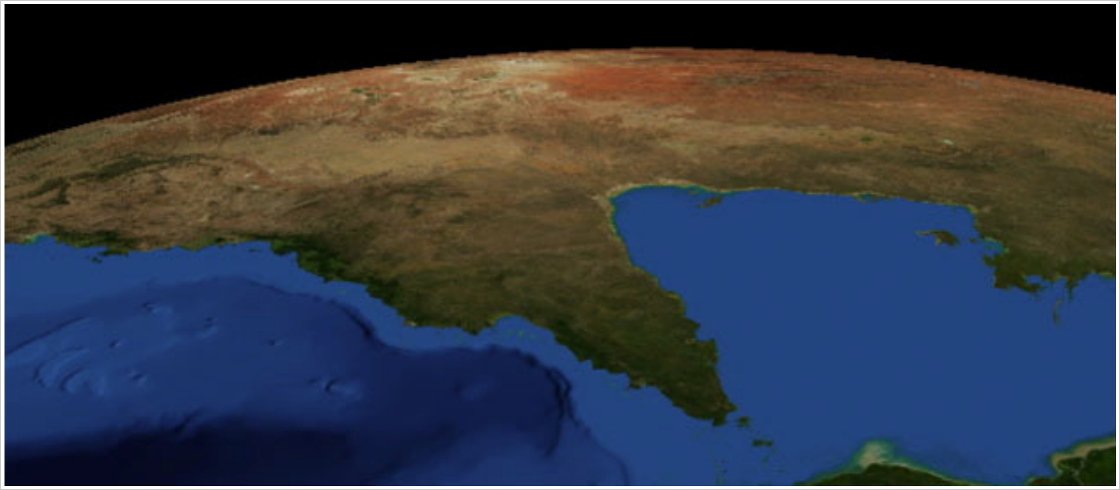
Changes in Earth's orbit have helped pace climatic change for millennia. Scientists are now trying to understand whether – and how – these changes remodeled the landscapes our ancient ancestors inhabited.



The idea that critical junctures in human evolution and behavioral development may have been shaped by environmental factors has been around since Darwin. Although various hypotheses and models have been proposed, refined, and/or abandoned for at least a century, the concept of **environmental determinism** and hominin evolution is still a hot topic today. While it is ultimately local-level environmental processes acting upon individual populations that is one of the driving forces of evolutionary change, such shifts are often framed within the context of much larger regional or global climatic trends.

Long-Term Records of Paleoclimate

Direct measurements of climate components such as temperature and precipitation only exist for the last century or two. To reconstruct climate over longer time-scales, scientists indirectly measure these components by analyzing various proxies, or indicators, that are sensitive to climatic or environmental parameters and preserved in the geological record. Proxy records from marine sediment and ice cores provide the basis for much of our understanding of past climate. These long-term and relatively continuous natural archives are often used as references for comparison with local terrestrial-based paleoenvironmental reconstructions. For example, the record of oxygen and hydrogen **isotope** ratios preserved in glacial ice, and oxygen isotope ratios in the shells of marine organisms such as **foraminifera** and **radiolaria**, provide a record of past sea levels, ice volume, seawater temperature and global atmospheric temperature (Figures 1 & 2). Air bubbles trapped in ice cores also provide a direct record of the past chemical composition of the atmosphere, particularly CO_2. Carbon isotope ratios of shells in marine cores are equally valuable for estimates of water circulation and atmospheric CO_2 concentrations. **Eolian** dust preserved in both marine sediment and ice cores has been correlated with climate and environmental conditions in the dust's source region, specifically as a proxy for aridity. Continuous ice cores from Greenland record back to over 100,000 years ago (Bender *et al*. 2002), while those from Antarctica extend back to ~800,000 years ago (Lambert *et al*. 2008). Thus, these records are relevant to the later members of the genus *Homo*, such as *H. erectus*, *H. heidelbergensis*, *H. neanderthalensis*, and *H. sapiens*. Documenting a much longer timescale, marine sediment cores have been collected across the globe, and composite records have been compiled that extend beyond the **Cenozoic**, thus covering the entire duration of the Primate fossil record (Zachos *et al*. 2001).

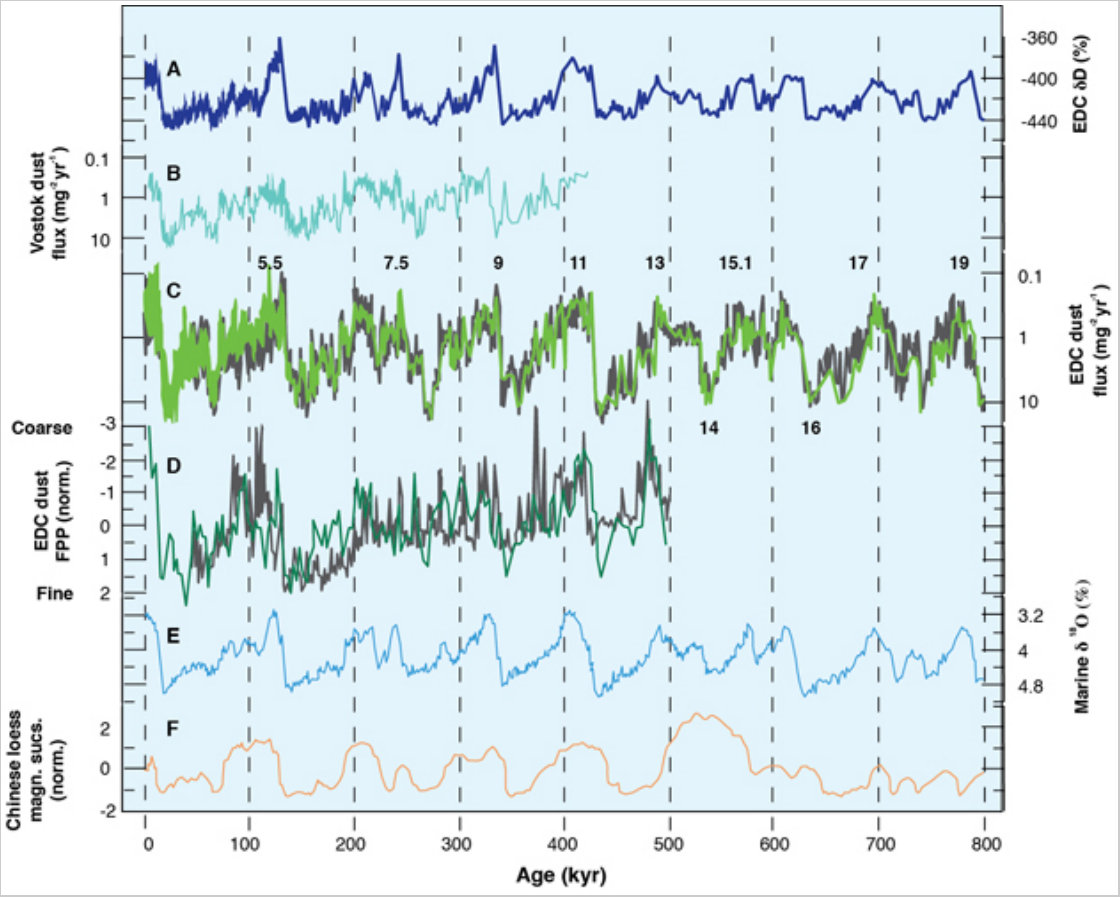


Figure 1: EPICA Dome C (EDC, Antarctica) data in comparison with other climatic indicators.

a, Stable isotope (δD) record from EDC. b, Vostok dust flux record. c, EDC dust flux records (numbers indicate Marine Isotope Stages). d, EDC dust size data expressed as fine particle percentage. e, Marine sediment $\delta^{18}O$ stack (proxy for global ice volume). f, Magnetic susceptibility stack record for Chinese loess. Peaks in most records depicted and odd MIS numbers indicate interglacial phases while troughs and even MIS numbers indicate glacial phases.

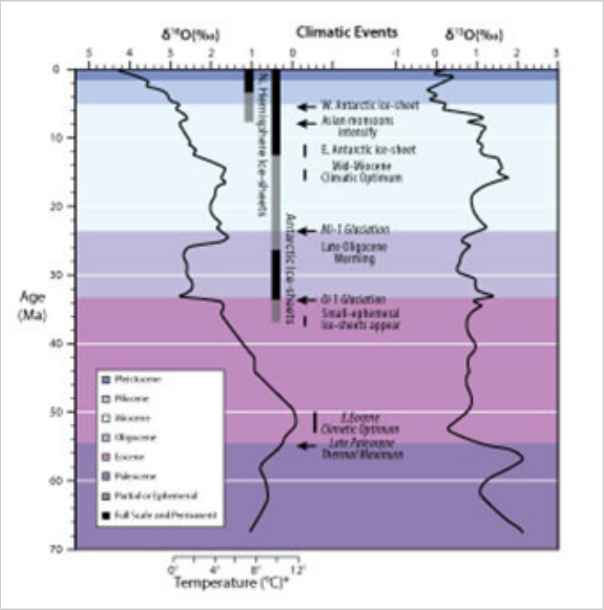


Figure 2: Global deep-sea oxygen and carbon isotope records.

Records for the Cenozoic based on data compiled from more than 40 DSDP and ODP sites with key climatic events indicated.

There are a variety of other important high-resolution paleoclimate records relevant to hominin evolutionary history, but these are temporally or spatially restricted compared to marine cores. For example, the variation in thickness and grain size in Chinese **loess** deposits are related to extensive periods of cold, dry, winter Asian **monsoon** winds stretching back over the last 7 million years (An 2000). **Speleothems** found in caves are also a rich archive of local paleoclimate information and, combined with **uranium-thorium dating**, can provide high-resolution records back to 500,000 years ago. Carbon and oxygen isotopic analysis as well as relative growth band thickness of speleothems have provided proxy data for local temperature, rainfall, aridity, and overlying vegetation (C_3 vs. C_4 plants) at hominin sites in South Africa, Europe, the Levant, and Asia (e.g., Wang *et al*. 1998, Bar-Matthews *et al*. 2003, 2010, Couchoud *et al*. 2009). Similar to the study of marine cores, an extensive arsenal of analytical methods have been applied to the study of lake cores, which serve as long, continuous archives of terrestrial climate change at annual to decadal scale for individual basins or watersheds. Existing lake cores in close proximity to paleoanthropological sites are typically restricted to the **Holocene** (e.g., Johnson & Odada 1996) but other cores in the Levant and Africa range from over 100 ka to 1 Ma (Koeberl *et al*. 2007, Scholz *et al*. 2007, Stein *et al*. 2011). Additional scientific drilling initiatives are exploring thick lacustrine deposits directly associated with **Plio-Pleistocene** paleoanthropological sites (Cohen *et al*. 2009)

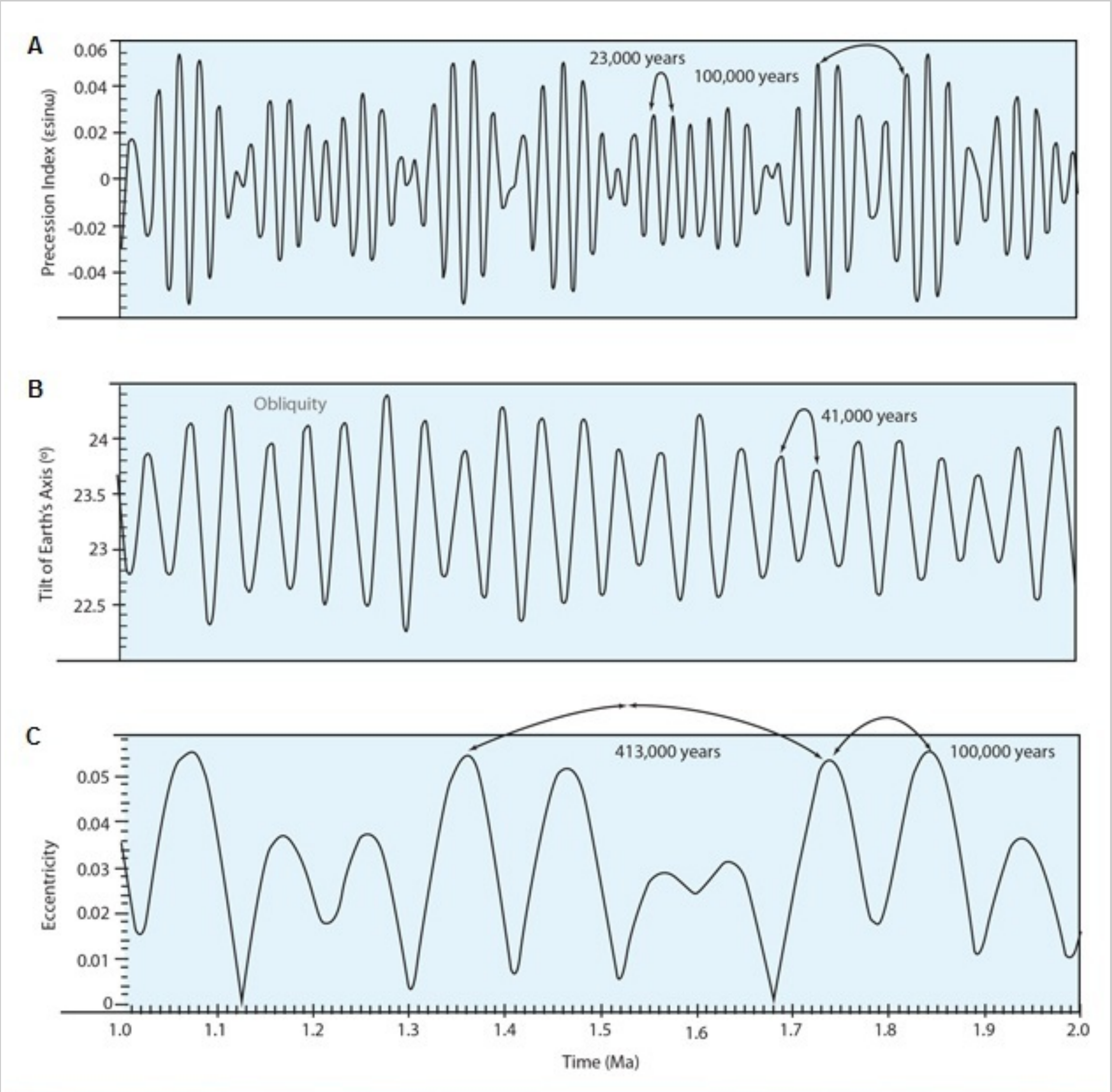
Astronomical Controls on Long-Term Climate Change

The pattern of incident solar radiation (insolation) received on the planet at a given place and time is an important factor in understanding both directional trends and variability observed in many paleoclimatic records, particularly those related to **Quaternary** ice ages (Hays *et al*. 1976, Laskar *et al*.

2004). Changes in insolation are, in turn, driven by Earth's natural orbital oscillations, termed **Milankovitch** cycles. The three elements of Milankovitch cycles are eccentricity, obliquity, and precession (Figure 3). Eccentricity describes the degree of variation of the Earth's orbit around the Sun from circular to more elliptical. Eccentricity has two main periodicities, one cycle with an average of ~100,000 years and a longer cycle with a periodicity of ~413,000 years. Obliquity describes the tilt of the Earth's axis in relation to its orbital plane, which ranges from 22.1–24.5 degrees with a periodicity of ~41,000 years. Precession describes the motion of the Earth's axis of rotation, which does not point towards a fixed direction in the sky through time. Instead, the axis of rotation describes a clockwise circle in space, like the spinning of a wobbling top, with a periodicity of 19,000–23,000 years (Animation 1).

Animation 1: Earth’s orbital precession.

Courtesy of NASA.


A
Precession Index (εsinω)
0.06
0.04
0.02
0
-0.02
-0.04
23,000 years
100,000 years
B
Obliquity
Tilt of Earth's Axis (º)
24
23.5
23
22.5
41,000 years
C
Eccentricity
0.05
0.04
0.03
0.02
0.01
0
413,000 years
100,000 years
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Time (Ma)

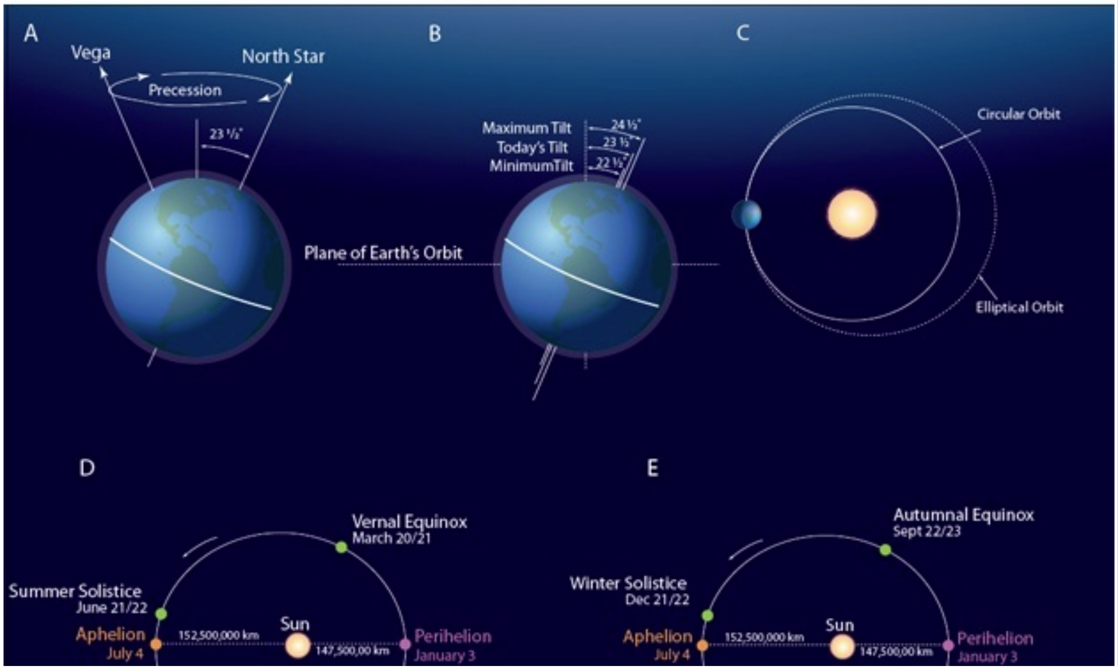

A
Vega
North Star
Precession
23 ½°
Plane of Earth's Orbit
B
Maximum Tilt
Today's Tilt
MinimumTilt
24 ½°
23 ½°
22 ½°
C
Circular Orbit
Elliptical Orbit
D
Vernal Equinox
March 20/21
Summer Solistice
June 21/22
Aphelion
July 4
152,500,000 km
Sun
147,500,00 km
Perihelion
January 3
E
Autumnal Equinox
Sept 22/23
Winter Solistice
Dec 21/22
Aphelion
July 4
152,500,000 km
Sun
147,500,00 km
Perihelion
January 3

Figure 3: Variations and schematic diagrams of Milankovitch cycles.

a, Precession and precessional index with a periodicity of ~23,000 years, with the amplitude of the cycles modulated at eccentricity periods of 100,000 years and 413,000 years ("variability packets"). b, The tilt of the Earth's axis with a periodicity of 41,000 years. c, The eccentricity of the Earth's orbit with periodicities of 100,000 and 413,000 years. d, Present position of the Earth in its orbit at different times of the year. e, Position of the Earth in its orbit at different times of year ~11,000 years in the future.

Solar radiation received at low-latitude is principally affected by variations in the cumulative effect of eccentricity and precession (eccentricity modulated precession), whereas higher latitudes are mainly affected by changes in obliquity. Since the Earth is tilted in its orbit, not all the Earth receives the same amount of energy, more energy being received at the equator than at the poles. Solar energy entering at a shallower angle at higher latitudes must travel further through the Earth's atmosphere compared to equatorial regions, reflecting some energy back to space. The same amount of solar energy also is spread over a larger area at higher latitudes. Increased tilt acts to amplify seasonal difference, while decreased tilt diminishes it. In its annual orbit, the Earth is currently closest to the sun (Perihelion) in early January, when the northern hemisphere is tilted away from the sun, and tilted towards the sun when the Earth is furthest from the sun (Aphelion) in early July (Figure 3d). Thus, **seasonality** is currently reduced in the northern hemisphere (but increased in the southern hemisphere) with the effect that northern hemisphere winters are not as cold as they could be, and summers are not as warm as they could be, a pattern that will be reversed in about 11,000 years (Figure 3e). Although the interactions between orbital parameters are major external drivers of paleoclimatic changes, the internal dynamics of the climate system also exert important controls on temporal and spatial patterns of environmental change. Furthermore, both **external and internal forcing** mechanisms can involve a complex series of feedbacks, and responses that may be linear or nonlinear, synchronous or delayed, or have a critical threshold ("tipping") point.

Paleoclimate and Hominin Evolution

One of the earliest examples that proposed a connection between climate-driven environmental change and hominin evolution was the "Savanna Hypothesis", which posited that the human lineage followed a simple trajectory from apelike to humanlike promoted by the challenges of an open savanna (Darwin 1871, Smith 1924, Bartholomew & Birdsell 1953). While we now know that there is no single "magic bullet" that is responsible for the multitude of anatomical and behavioral changes documented in the hominin record, the concept that certain changes in the human lineage may have evolved in open habitat settings has persisted. With the establishment of the marine paleoclimatic framework, researchers began to evaluate hominin evolutionary processes and events in the context of global climatic oscillations, particularly the onset of Northern Hemispheric Glaciation (NHG) ~2.7 Ma. The "Turnover Pulse Hypothesis" championed by paleontologist Elisabeth Vrba (Vrba 1988, 1995) proposed that a synchronous change in hominins, such as the origins of the genus *Homo*, and other African mammalian lineages, particularly speciation and extinction events in **bovids**, was caused by a shift from warm, moist conditions to cooler, drier, and more open habitats associated with a sharp transition in the marine oxygen isotope record associated with the onset of NHG (Figure 4). Other studies have since indicated that the record at specific East African hominin sites show either no faunal turnover at this time (e.g., Kingston *et al.* 1994) or that there were multiple pulses or prolonged periods of turnover set with a more gradual shift from forested to more open habitats (Behrensmeyer *et al.* 1997).

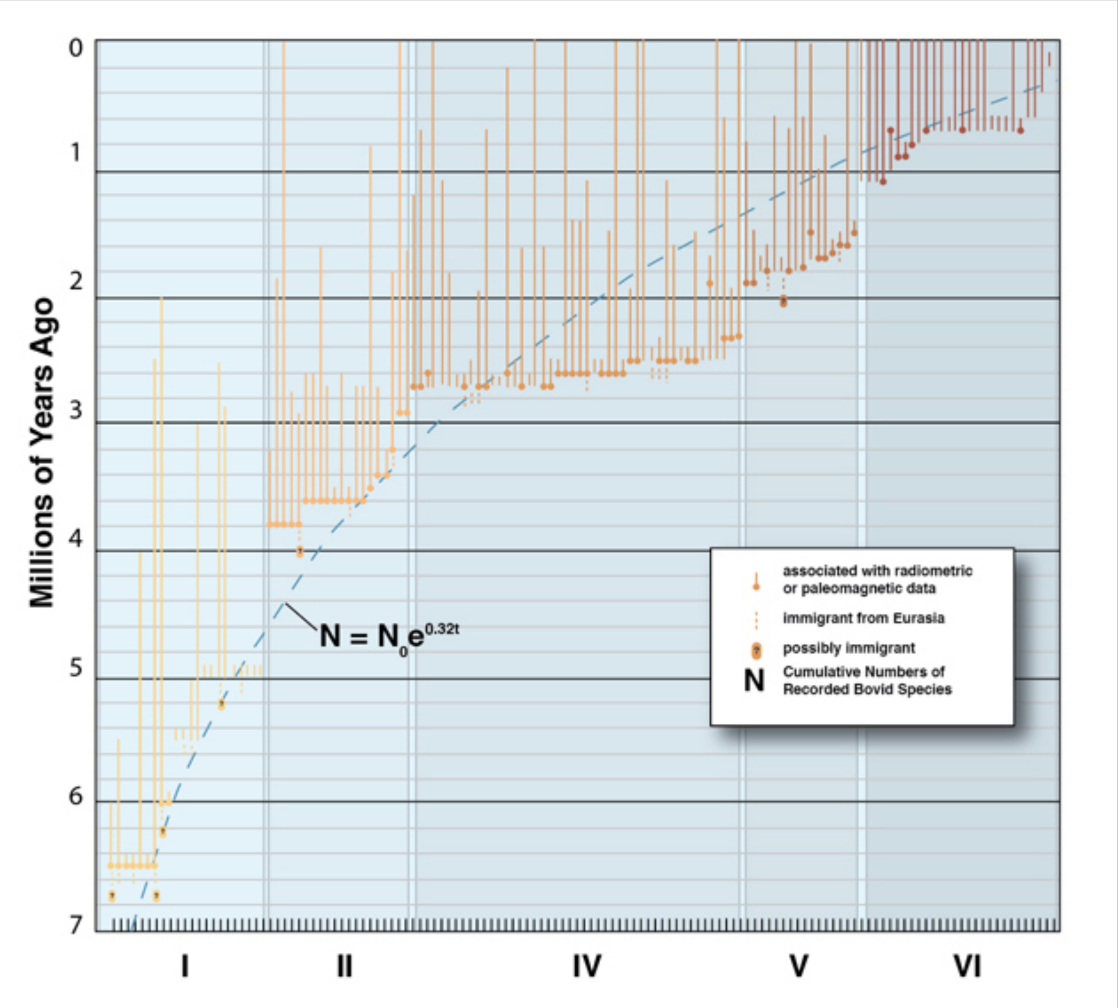


Figure 4: Range chart of first and last appearance datums (FAD/LAD) of African fossil bovids spanning the last 7 Myr.

The dashed line represents a theoretical "null hypothesis" assuming a uniform rate of faunal turnover (speciation) set at 32% per million years. Notable faunal “turnover pulses”, clusters of origination and extinction events, which occurred near 2.8 Ma and 1.8 Ma were also associated with appearances of arid-adapted fauna.

A seminal study of **terrigenous** dust in marine cores off the coast of Africa by paleoceanographer Peter deMenocal suggested that subtropical African climate oscillated between markedly wetter and drier conditions, paced by Earth's orbital variations, with step-like increases in climate variability and aridity near 2.8, 1.7 and 1.0 Ma (deMenocal 1995, 2004). These steps were coincident with changes in the dominant orbital cycles from precession to obliquity to eccentricity, and with the onset and intensification of high-latitude glacial cycles, respectively. Compared to the African fossil and geological record, these time periods also coincided with proposed diversification points in the hominin lineage (2.9-2.4 Ma), paleoenvironmental evidence for drier habitats and the expansion of *Homo* out of Africa (1.8-1.6 Ma), and the extinction of the *Paranthropus* lineage, the broadened range of *Homo erectus*, and the establishment of more modern savanna ecosystems (1.2-0.8 Ma) (Figure 5). In addition to unidirectional shifts, deMenocal also highlighted the importance of "variability packets" of high- and low-amplitude paleoclimatic variability lasting 10,000 to 100,000 years in duration, paced by the orbital eccentricity modulation of precession (Figure 3a). These alternating periods of relative paleoclimatic stability (low eccentricity) and instability (high eccentricity) as a mechanism for introducing genetic variance to natural selection are a key component of the "Variability Selection Hypothesis" (Potts 1998), which proposes that the wide variability in adaptive settings over time ultimately favored complex adaptations that were responsive to novel conditions (i.e., the evolution of adaptability).

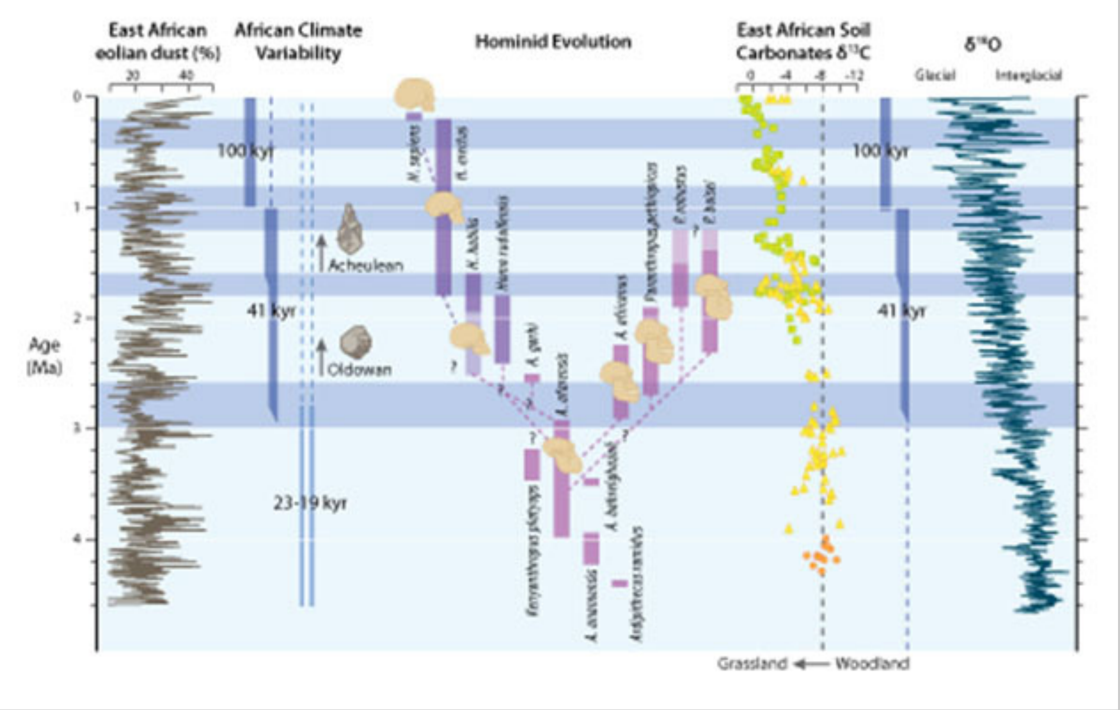


Figure 5: Summary diagram of important paleoclimatic and hominin evolution events during the Plio-Pleistocene.

Gray bands indicate periods when African climate became progressively more arid after step-like shifts near 2.8 (±0.2) Ma and subsequently after 1.7 (±0.1) Ma 1.0 (±0.2) Ma coincident with the onset and intensification of high-latitude glacial cycles. From left to right: Percent of terrigenous dust in ODP site 721/722 with corresponding shifts in the dominant periodicity of the dust flux linked to precessional variability (23-19 kyr) and characteristic glacial cycles (41 kyr and 100 kyr). Approximate first and last appearance datums and possible relationships among hominin taxa. Soil carbonate carbon isotopic data from East African hominin localities documenting a progressive shift from woodland to grassland vegetation. Composite benthic foraminfera oxygen isotope record illustrating the evolution of high-latitude glacial cycles and dominant periodicity of glacial variability.

Studies of East African lake records by geologist Martin Trauth and colleagues have also focused on critical intervals near 2.6, 1.8 and 1.0 Ma and documented the presence of large, but fluctuating lakes, indicating consistency in wetter and more seasonal conditions every 800,000 years (Trauth *et al*. 2005, 2007). African monsoon intensity correlates with precession-paced insolation, and increased polar ice-volume acts to accentuate the pole-Equator thermal gradient, which leads to a north-south compression of the **Intertropical Convergence Zone** (ITCZ), the major control of monsoonal precipitation patterns in Africa. Associated with major glacial events near 2.6, 1.8 and 1.0 Ma, Trauth and colleagues propose that global climate changes led to increased seasonality and regional climate sensitivity to insolation, which resulted in packages of precessionally forced alterations between episodes of large lakes and extreme aridity, possibly as rapid as every ~10,000 years during eccentricity maxima (Trauth *et al*., 2003; Kingston *et al*., 2007). They propose that these occurred during periods of eccentricity maxima every 800,000 years since 2.7 Ma (similar to deMenocal's variability packets). While some East African lake records provide strong evidence for this pattern (e.g., Kingston *et al*. 2007), it may not be universal across space or time (Scholz *et al*. 2007). Ultimately, this hypothesis proposes that periods of dramatic climatic oscillations between 2.7–2.5 Ma, 1.9–1.7 Ma, and 1.1–0.9 Ma led to rapid expansion then subsequent contraction/fragmentation of hominin habitats at precessional timescales with associated dispersal events and **vicariance** in the hominin lineage (Figure 6).

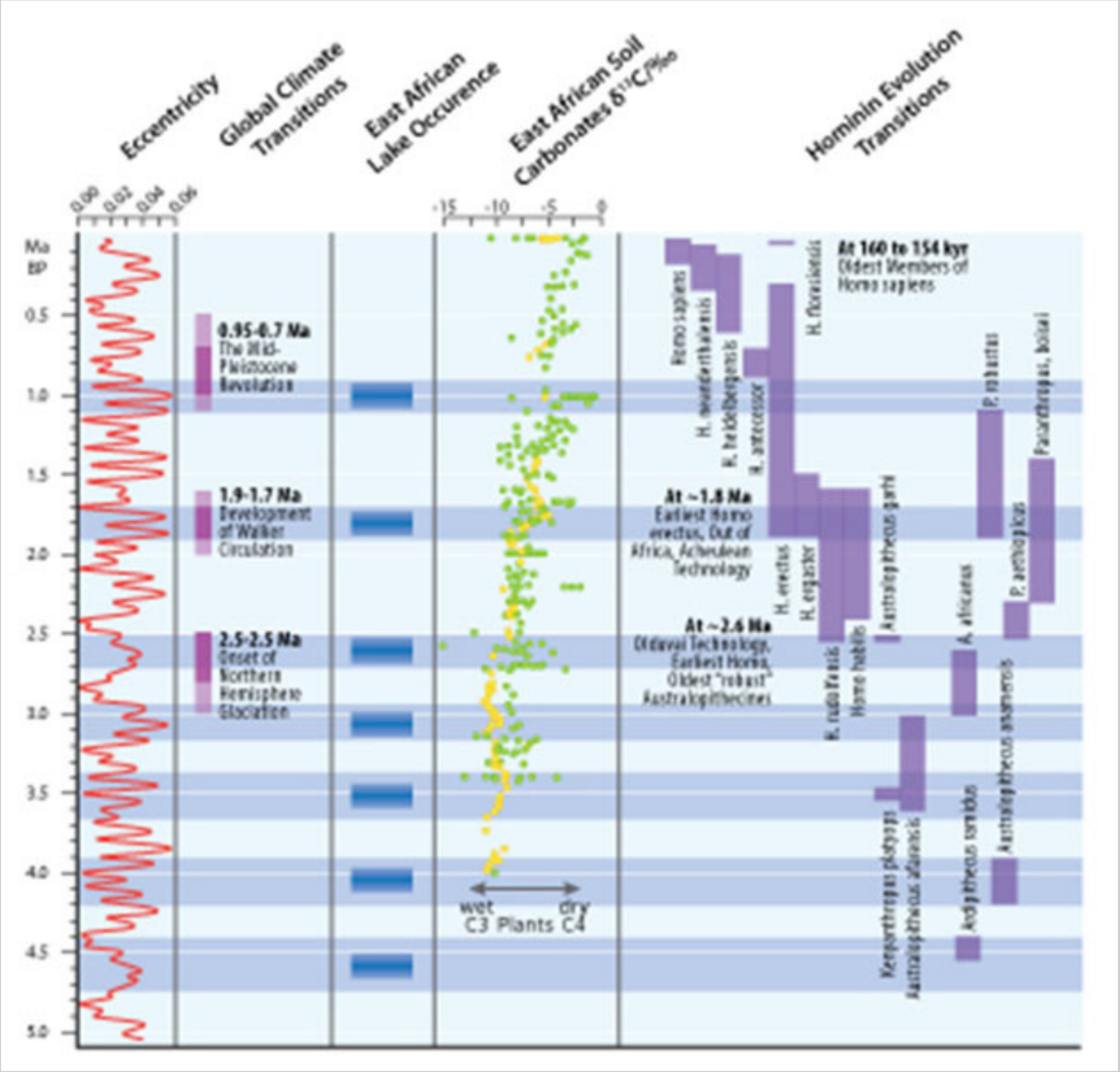


Figure 6: Summary diagram of global climate transition, East African lake occurrences and soil carbonate records, and hominin evolution.

East African lake occurrences are suggested to cluster during eccentricity maxima prior to 2.7 Ma (prior to NHG) and during periods of global climate transitions associated with eccentricity maxima after 2.7 Ma (post NHG). Note that lake phases do not occur during all eccentricity maxima and that some occur during eccentricity minima. Hominin FAD/LADs should be considered approximate.

Discussion and Challenges

It seems intuitive that large-scale shifts and short-term variability in paleoclimate altered local to regional hominin habitats and resource availability that ultimately led to selection pressures on our fossil ancestors. However, climate systems are markedly complex and dynamic, and may change drastically over relatively short distances. It is important to maintain a critical perspective on the types, quality, and scale of empirical paleoenvironmental data, particularly when the volume and temporal resolution of proxy data far exceeds that of the hominin fossil record itself (Kingston 2007, Behrensmeyer *et al.* 2007). For instance, error-bars on hominin **FADs** and **LADs** that indicate the probability of true origination or extinction events are rarely reported (e.g., Figures 5 & 6). When accounting for influences such as sample size and geochronological uncertainties, the potential mismatch between a taxon's actual origination and its documented FAD in the fossil record (or extinction and LAD) is likely on the order of tens to hundreds of thousands of years. All hypotheses that propose causal links between paleoclimatic change and hominin evolution must ultimately reconcile global patterns with local responses, and extend far beyond a general temporal correlation between environmental change and an evolutionary event. Criteria for testing hypotheses of environmental forcing include a highly resolved time scale for the various records to validate cause-before-effect order, a robust correspondence between multiple lines of proxy evidence that shows similar patterns or trajectories, the ability to rule out alternative (non-environmental) hypotheses, and ultimately, a causal mechanism. Nevertheless, once the assumptions and limitations of utilizing global paleoclimatic data are appreciated, the almost dizzying array of natural archives of the past provide paleoanthropologists with a highly-resolved contextual framework within which they can develop research questions and test hypotheses.

Glossary

Bovids: Members of the family Bovidae that includes antelopes, oxen, goat and sheep. Unbranched horns made up of a layer of keratin surrounding a bony core are one of the defining characteristics.

C_3 & C_4: Different pathways for carbon dioxide assimilation during photosynthesis. C_3 plants include trees, shrubs and cool-climate grasses (~95% of plant species). C_4 plants include warm-climate grasses and grains, and are advantageous under conditions of high heat and light, and low carbon dioxide levels.

Cenozoic: The geological era lasting from ~65 million years ago to the present.

Environmental determinism: The view that changes in physical, abiotic environmental factors are the dominant influence on evolution, as opposed to stochastic (i.e., random), social, or cultural factors.

Eolian: Processes related to the activity of the winds.

External and internal forcings: External forcing mechanisms involve agents acting from outside the climate system (e.g., Milankovitch cycles). Internal mechanisms operate within the climate system itself (e.g., mountain building, plate tectonics, volcanic activity, ocean circulation, atmospheric composition).

FAD/LAD: Abbreviation of first/last appearance datum, the first/last appearance of a species in the geological record.

Foraminifera: A large and diverse group of, single-celled aquatic organisms (mainly marine) that construct their shells from calcium carbonate.

Holocene: The geological epoch lasting from ~11,700 years ago to the present.

Intertropical Convergence Zone (ITCZ): The equatorial region where the trade winds of both hemispheres come together and are associated with high precipitation. As the ITCZ is tethered to the zone of maximum solar insolation, its location migrates north and south of the equator with the seasons.

Isotope: Variants of a particular element that have the same number of protons, but different number of neutrons.

Loess: A deposit composed primarily of homogeneous, nonstratified, wind-blown silt.

Milankovitch: Milutin Milankovitch (1879-1958), a Serbian mathematician who proposed that climatic changes, particularly ice ages, were the result of variations in the Earth's orbital elements.

Monsoon: A wind system whose direction changes with the seasons. Often associated with seasonal precipitation.

Plio-Pleistocene: A combination of the Pliocene and Pleistocene epochs that lasted from ~5.3 million years ago to ~11,700 years ago (the beginning of the Holocene)

Quaternary: The geological period that includes the Pleistocene and Holocene epochs, lasting from ~2.6 million years ago to the present. Prior to 2009 the beginning of the Quaternary and Pleistocene was set at ~1.8 million years.

Radiolaria: A large and diverse group of single-celled marine organisms that construct their shells from silica.

Seasonality: Changes in timing, duration, or intensity of the within-year distribution of climatic elements, but not in total annual amounts (e.g., solar insolation, precipitation).

Speleothem: A mineral deposit, typically calcium carbonate, that precipitates from solution in a cave (e.g., stalagmites and stalactites).

Terrigenous: Material derived from land.

Uranium-thorium dating: An absolute dating technique based on the natural radioactive decay of uranium to thorium.

Vicariance: The separation of a population through the development of a natural biogeographical barrier.

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