CHAPTER FOUR

Global and African Regional Climate during the Cenozoic

SARAH J. FEAKINS AND PETER B. DEMENOCAL

The last 65 Ma of Earth's history, the Cenozoic, has been a time characterized by significant climate change. Major global changes included massive tectonic reorganization, a reduction in atmospheric pCO_2 (Pagani et al., 1999; Pearson and Palmer, 2000), and a dramatic cooling of global climate, plunging the world from generally warm conditions into the repeated glacial-interglacial cycles of the ice age (Zachos et al., 2001). Deep-sea oxygen isotope records record global cooling of up to 8°C in the early Cenozoic, heralding the development of major ice sheets on Antarctica from 35 Ma, which further intensified the global cooling trend and culminated in cyclical Northern Hemisphere glaciation during the past 3 Ma (figure 4.1). Many events in global tectonics and high latitude climate had significant effects on Cenozoic climate evolution. These are well described elsewhere (e.g., Kennett, 1995; Denton, 1999; Zachos et al., 2001) and are summarized in figure 4.1.

In this chapter, we focus on three revolutions in climate research that have dramatically altered our perception of global and African climate. First, the discovery that large magnitude climate events occurred abruptly, sometimes in as little as decades, has prompted high-resolution paleoclimate reconstructions and new conceptions of climate dynamics, revealing significant climate variability at times that were previously thought to be quiescent (e.g., the Holocene). On longer timescales, high-resolution oxygen isotope stratigraphies have also revealed transient events in the early Cenozoic (Zachos et al., 2001). These discoveries have revolutionized theories of climate change and demonstrated the need for high-resolution reconstruction of climate variability on 10^0- to 10^5-year timescales.

Second, recent climate studies have revealed significant tropical climate variability. Modern observational climate data have indicated that the largest mode of global interannual climate variability is the El Niño Southern Oscillation (ENSO) in the tropical Pacific (Ropelewski and Halpert, 1987; Trenberth et al., 1998). Large amplitude tropical environmental variability has also been reconstructed in the paleoclimate record. In particular, revised estimates of tropical sea surface temperatures (SSTs) during global cool and warm events have revealed significant tropical sensitivity to global climate change (e.g., Pearson et al., 2001; Lea et al., 2003). Revised tropical SST reconstructions have implications both for local climate interpretations and for global dynamical predictions, leading to new perspectives on the nature of Cenozoic climate change.

Third, the role of the tropics in global climate change has been reconceptualized. Rather than being a passive responder to changes in the high-latitude cryosphere, tropical climate variability may be at least partially decoupled from high-latitude climate. For example, there is considerable evidence that precessional variations in insolation may directly influence the intensity of African precipitation, independent of high-latitude climate variability (Rossignol-Strick, 1983; Partridge et al., 1997; Denison et al., 2005). The tropics may even have driven global climate change. For example, ENSO generates global teleconnections that have been observed in the instrumental record (Cane and Zebiak, 1985; Cane and Clement, 1999), and evidence for tropical initiation of past global climate changes comes from both paleoclimate and modeling analyses (Linsley et al., 2000; Clement et al., 2001; Hoerling et al., 2001; Yin and Battisti, 2001). This chapter provides a synthesis of climate data from a tropical perspective that offers new insights into aspects of Cenozoic African environmental change.

Modern African Climate

Precipitation is the critical interannual variable in African climate. Seasonal variations in the position of the Intertropical Convergence Zone (ITCZ) exert a significant control on the seasonal pattern of precipitation maxima across much of Africa. Figure 4.2 shows the major atmospheric circulation regimes for average conditions in July/August and January that illustrate common climatic zones and provide a basis for understanding climatic variability (Nicholson, 2000). Distinct atmospheric circulation systems affect North Africa, West and Central Africa, East Africa, and southern Africa; they are separated in large part by the ITCZ. These regions experience characteristic patterns of interannual variability, teleconnections, and surface characteristics (Janowiak, 1988; Semazzi et al., 1988).

The northern coast of Africa has a Mediterranean climate receiving winter precipitation supplied by the midlatitude

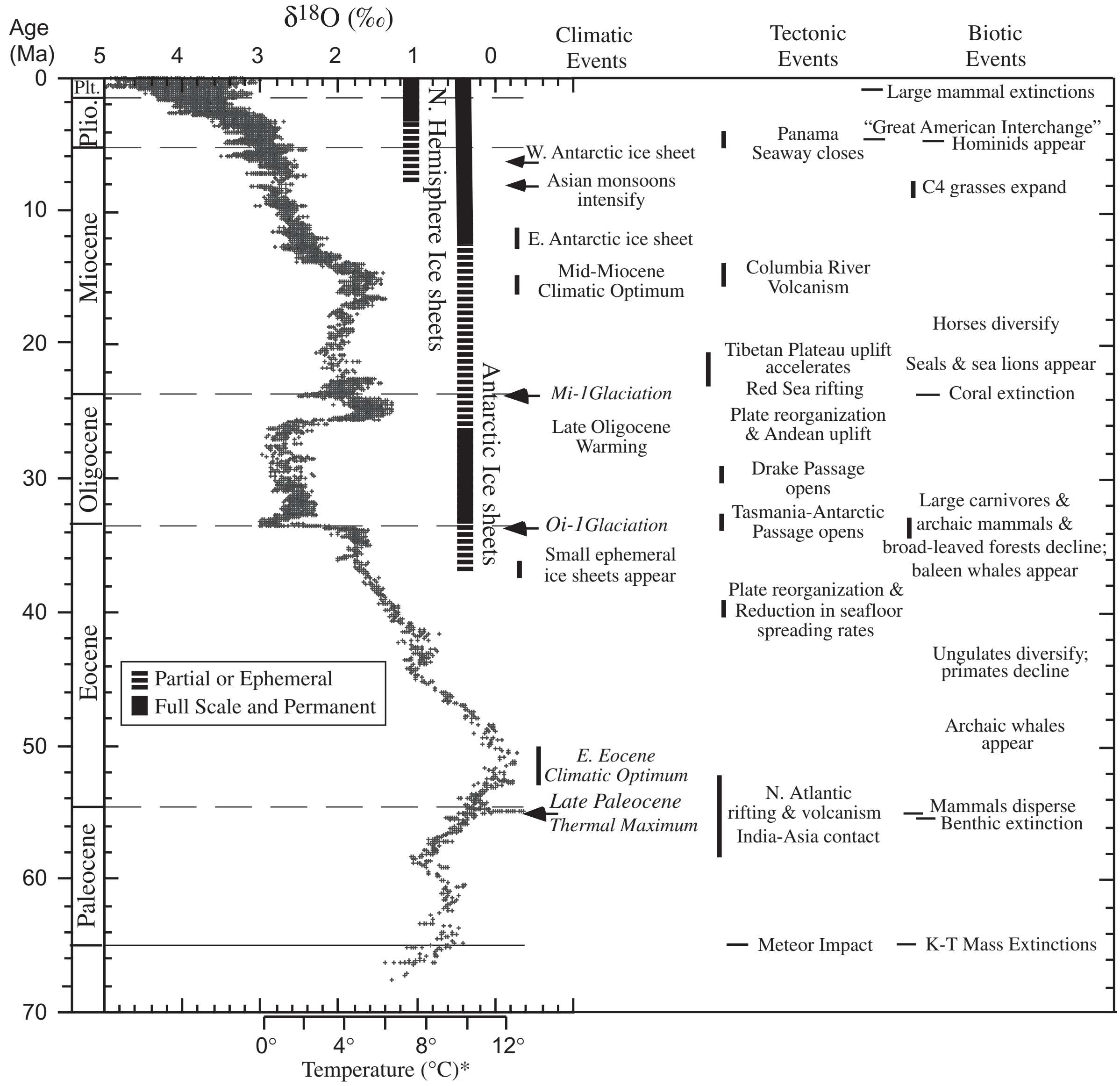

FIGURE 4.1 Global deep-sea oxygen isotope records for the last 65 Ma based on data compiled from more than 40 DSDP/ODP marine sites, together with some key tectonic and biotic events. The temperature scale refers to an ice-free ocean and thus only applies prior to the onset of large-scale glaciations (~35Ma). From the early Oligocene to the present, much of the oxygen isotope variability reflects changes in ice volume. Reprinted in part with permission from Zachos et al. (2001). © 2001 AAAS.

westerlies (Nicholson, 2000). Interannual to interdecadal variability is influenced by regional and global atmospheric teleconnections associated with the North Atlantic Oscillation (Hurrell, 1995) and to a variable extent by ENSO (Knippertz et al., 2003). Greenland ice core data indicate that these patterns of variability have persisted for several hundred years (Dansgaard et al., 1993).

West Africa is dominated by summer monsoonal precipitation associated with the northward migration of the ITCZ (figure 4.2). Tropical Atlantic SSTs have been shown to exert primary control on the strength of West African monsoon and Sahelian precipitation at interannual to interdecadal timescales (Rowell et al., 1995; Giannini et al., 2003). Warm SST anomalies in the Gulf of Guinea reduce the land-sea temperature contrast and weaken the monsoon. Convection cells remain over the ocean, increasing rainfall to coastal regions and decreasing rainfall to the Sahel. Variations in continental heating also influence the land-sea temperature contrast and strength of the monsoon on millennial timescales (deMenocal et al., 2000; Liu et al., 2003). Central African rainfall is also negatively correlated with equatorial Atlantic SSTs but positively correlated with subtropical Atlantic SSTs (Nicholson and Entekhabi, 1987; Camberlin et al., 2001), with seasonal rainfall maxima associated with the passage of the ITCZ (figure 4.2). The hydrogen isotopic composition of plant leaf wax biomarkers in the Congo Fan indicate that this relationship has persisted for the past 20 ka (Schefuss et al., 2005).

Southern Africa has a strong precipitation gradient from >1,000 mm per year in the east to <20 mm per year in the west (Nicholson, 2000). Most precipitation falls in the austral summer as convective rainfall, particularly in the southeast. In the southwest, the precipitation pattern is more complex, with rainfall maxima associated with the seasonal peak in

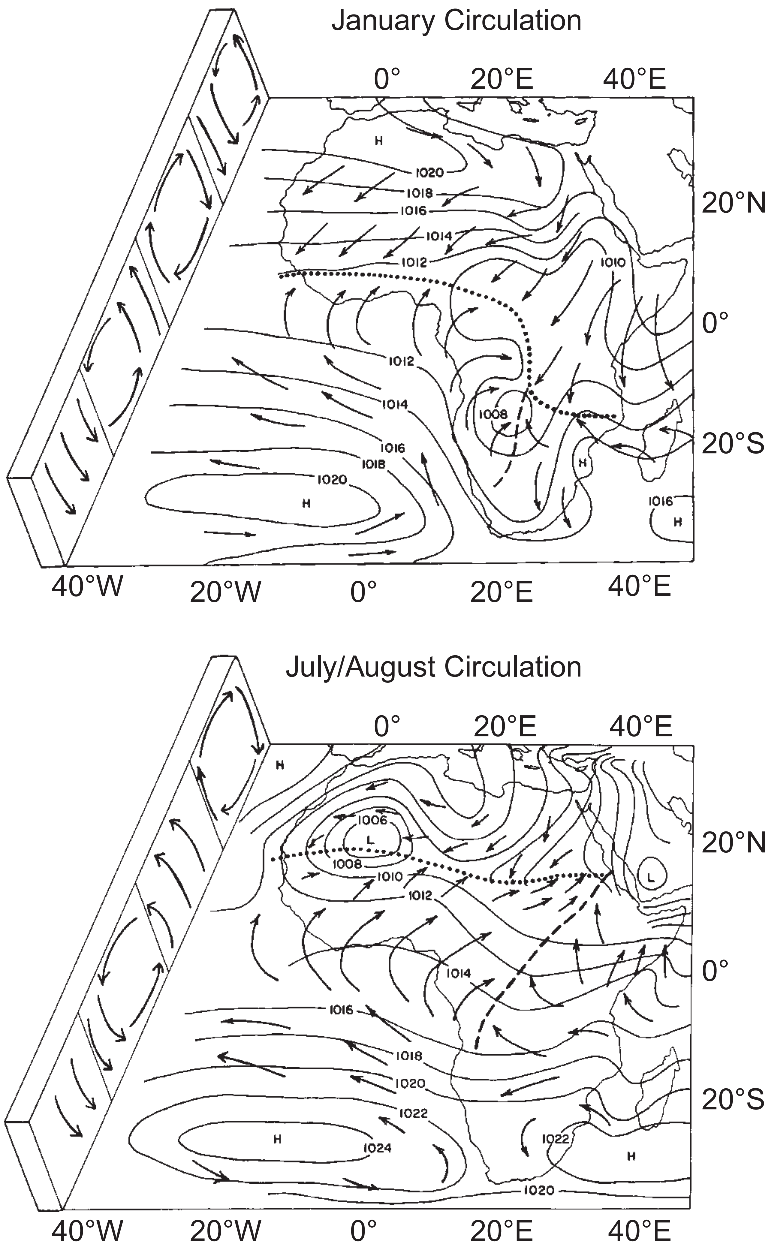

FIGURE 4.2 Schematic of the general patterns of winds, pressure, and convergence over Africa. Dotted lines indicate the ITCZ; dashed lines indicate other convergence zones. Reprinted with permission from Nicholson (2000). © 2000 Elsevier.

SSTs in Benguela coastal regions. Summer heating creates low pressure over central Africa that pulls in moisture from the western Indian Ocean. Significant interannual variability in precipitation is dominated by western Indian Ocean SSTs, with variability that is strongly related to ENSO in the Pacific (Cane et al., 1994; Goddard and Graham, 1999; figure 4.3). El Niño years are anomalously dry in southern Africa between December and February. These interannual observations suggest that past variations in Indian and Pacific SSTs are likely to have had a significant influence on southern African rainfall, particularly in the southeast, whereas variations in the strength of upwelling and the Benguela current may have been more important for southwest African climate.

East Africa receives most of its precipitation in April to March and September to November, associated with the biannual passage of the ITCZ and seasonally reversing winds (figure 4.2). The primary moisture source is the central Indian Ocean via the southeasterly trade winds. Although the relative humidity is moderately high, precipitation in East Africa is low because of regional atmospheric circulation (Rodwell and Hoskins, 1996). Subsidence associated with the Indian Monsoon system inhibits convection, and the Ethiopian highlands constrict the southeasterly flow, resulting in southwesterly moisture divergence feeding the Indian Monsoon. On interannual timescales, Indian and Pacific ocean SSTs determine precipitation variability (figure 4.3; Goddard and Graham, 1999). These anomalous features of East African circulation suggest that uplift of the Himalayas and Ethiopian Highlands would have driven a gradual aridification of equatorial East Africa during the Cenozoic with superimposed climate variability resulting from SST variability in the Indian and Pacific oceans.

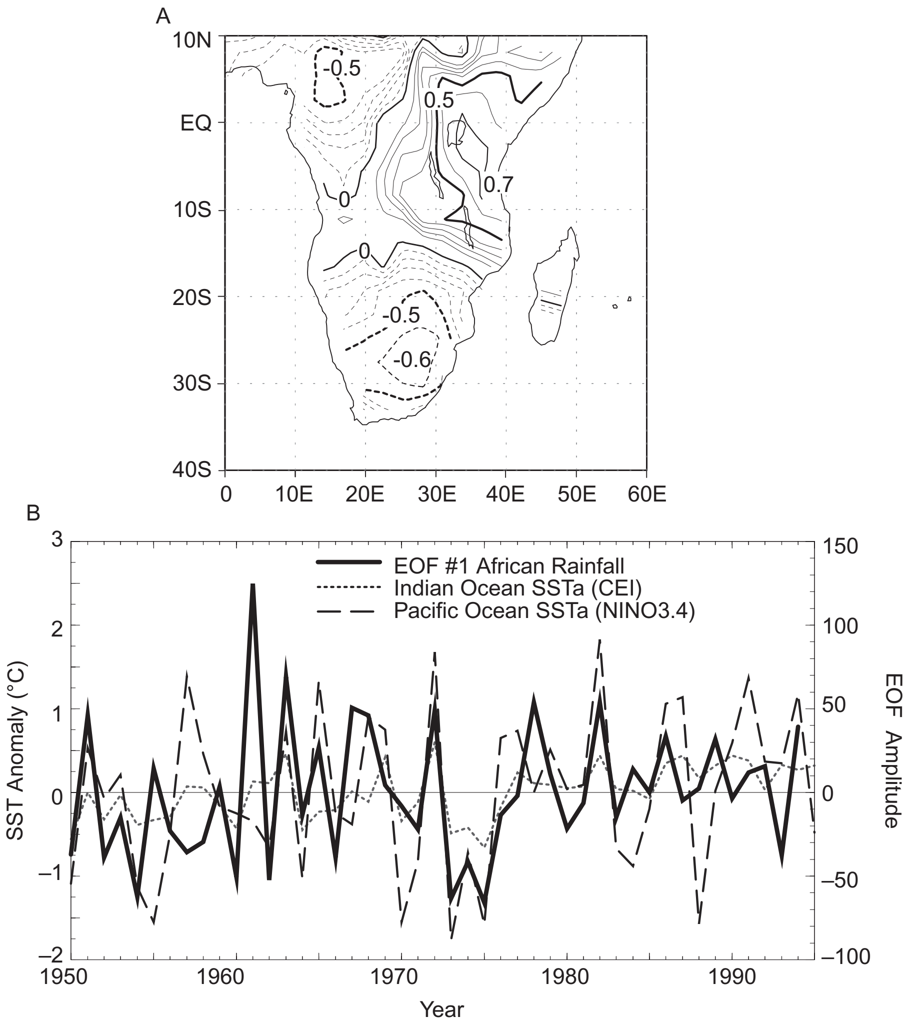

FIGURE 4.3 SSTs and southern African climate (from Goddard and Graham, 1999). A) First empirical orthogonal function (EOF) of observed rainfall anomalies for November to December–January 1950–1995, plotted as correlations between the rainfall anomalies and the EOF temporal function. B) Time series for amplitude of first EOF of African rainfall (thick solid line), amplitude on right axis. Also plotted are time series of sea surface temperature (SST) indices for the Indian Ocean, central equatorial Indian index (CEI; 15°S–0; 50°E–80°E, dotted line) and the Pacific Ocean, NINO3.4 (5°S–5°N; 170°W–110°W, dashed line).

ENSO SST variability in the tropical Pacific is the dominant mode of global interannual (2–7 yr) climate variability, with well-documented regional and global climate effects. El Niño events most strongly influence East and South Africa with strengthened upper westerly winds that lead to decreased rainfall in South Africa (December–March) and increased rainfall in East Africa (October–December—see figure 4.3; Hastenrath et al., 1993). North and West Africa are partially influenced by ENSO variability. In the Sahel, El Niño events tend to correlate with dry conditions (July–September). Sustained El Niño or La Niña–like conditions may also explain global climate patterns during paleoclimate events such as the warm, wet mid-Pliocene or be a possible trigger mechanism for abrupt climate events such as the Younger Dryas (Clement et al., 2001; Molnar and Cane, 2002; Wara et al., 2005; Ravelo et al., 2006). Observational and modeled studies of modern seasonal to interdecadal variability have provided important insights into the regional and global climate parameters that influence African climate variability. These fresh perspectives may provide new answers about the global signature of Cenozoic paleoclimate events, particularly in Africa.

Cenozoic Climate Change

ABRUPT EVENTS IN THE PALEOCENE

One of the most dramatic events of the entire Cenozoic occurred in the late Paleocene (ca. 55 Ma). Antarctic and deep ocean temperatures rose by more than 6°C in less than 10 ka, creating a dramatic warming event, the Paleocene-Eocene Thermal Maximum (PETM) that lasted for 50 ka (figure 4.1; Stott and Kennett, 1990). This abrupt warming took place in an already warm era when global carbon dioxide levels were extremely high (>2,000 ppm), the poles were ice free (Zachos et al., 2001), sea levels were high, and a large marine transgression covered most of northern Africa (65–50 Ma; Le Houerou, 1997). This large-amplitude, abrupt event has been documented in a Tunisian record and would likely have had a significant impact on nearby continental climate (Bolle et al., 1999). These dramatic climate events have been linked to the Cretaceous-Paleogene extinction event and subsequent stabilization and rapid speciation, particularly within 10–100 ka after the PETM, when most of the modern orders of mammals appeared (Gingerich, 2004).

REVISED TROPICAL TEMPERATURES IN THE EOCENE

The Eocene is thought to be the warmest epoch of the Cenozoic, although climate data for this period are sparse, especially in Africa. Warm deep ocean temperatures (>10°C) are recorded in benthic foraminiferal oxygen isotopes during the early Eocene climatic optimum (54–50 Ma; figure 4.1). Although temperatures had risen, pCO_2 levels had dropped down to 700–900 ppm from their Paleocene high of >2,000 ppm. Early estimates of tropical temperatures based on foraminiferal oxygen isotopes suggested unexpectedly cool temperatures (15°–23°C), resulting in meridional temperature gradients that could not be reconciled with known dynamical mechanisms (Zachos et al., 1994). Cool tropical temperature estimates may have been biased by diagenesis or winter foraminifera growth, and recently revised tropical SST estimates (>28°C) are consistent with dynamic predictions based on high-latitude warming (Kobashi et al., 2001; Pearson et al., 2001). African continental environments appear to have been warm and wet during the Eocene. Bauxite, iron, and lateritic deposits at paleolatitude 5°–15°N indicate a humid Eocene climate (Guiraud, 1978). Paleobotanical remains from a middle Eocene crater lake in Tanzania (12°S) suggest high rainfall (640–780 mm per year) and woodland vegetation (Jacobs and Herendeen, 2004). A generally warm and wet African climate during the Eocene is consistent with a strong moisture source to the atmosphere provided by warm SSTs.

OLIGOCENE ANTARCTIC GLACIATION AND SOUTHERN AFRICAN CLIMATE

Significant southern African climate change at the Eocene-Oligocene boundary is indicated by seismic evidence from the Zaire (Congo) deep-sea fan. Marine sediments indicate a shift from pelagic sedimentation during Eocene greenhouse conditions to dramatically increased continental erosion associated with uplift in southern Africa and Oligocene global cooling (Anka and Séranne, 2004). The growth of the first permanent Antarctic ice sheet (35–26 Ma; figure 4.1) led to the development of the cold Benguela Current and associated increase in southern African aridity. Productivity proxies indicate that Benguela coastal upwelling intensified in the mid-Miocene with the second phase of Antarctic ice sheet growth (Diester-Haass et al., 1990; Robert et al., 2005). Dust records indicate that southwest African aridity increased after 9.6 Ma, and between 8.9 and 6.9 Ma, with significant variability after 6.5 Ma closely associated with the intensity of Benguela upwelling and ultimately the history of Antarctic glaciation (Robert et al., 2005). These marine records indicate that southwest African aridity developed in the Oligocene and Miocene, closely related to the intensity of the Benguela upwelling, which strengthened at times of increased equator-to-pole temperature gradients.

MID-MIOCENE CLIMATE CHANGE IN EAST AFRICA

The significant climate events that affected East Africa in the mid-Miocene are relatively well documented compared to earlier ones. Forested conditions in the early Miocene gave way to mixed grassland and forest in the mid-Miocene. Fossil plants indicate the earliest C3 grasslands in Africa at Fort Ternan, Kenya, ca. 14 Ma (Retallack, 1992). Isotopic studies confirm that mid-Miocene grasslands were C3 (Cerling et al., 1997a; Feakins et al., 2005; see figure 4.4). Wet rain forest survived in many areas, including in northwestern Ethiopia (8 Ma; Yemane et al., 1987) and in the Tugen Hills, Kenya (8–6 Ma; Kingston et al., 2002) indicating mixed savannah and forest habitats across East Africa.

C4 grasses appear in East Africa in the mid-late Miocene (Cerling et al., 1997b). C4 grasses replace C3 plants as the most significant dietary component of northeast African grazing mammals between 8 and 6 Ma (Cerling et al., 1997b). Faunal assemblages at Lothagam, in the western Turkana Basin, also support a transition from C3 forest to a mixed C3 and C4 savanna mosaic between 8 and 4 Ma (Leakey et al., 1996). However, soil carbonate and leaf wax biomarker isotopic data indicate that C3 vegetation remained a significant component of regional vegetation during the Pliocene (Wynn, 2004; Feakins et al., 2005; figure 4.4). These vegetation reconstructions indicate that C4 plants may only have expanded to become a dominant component of the landscape in the late Pliocene and Pleistocene, much later than they appeared as a significant component of the diets of certain grazing mammals.

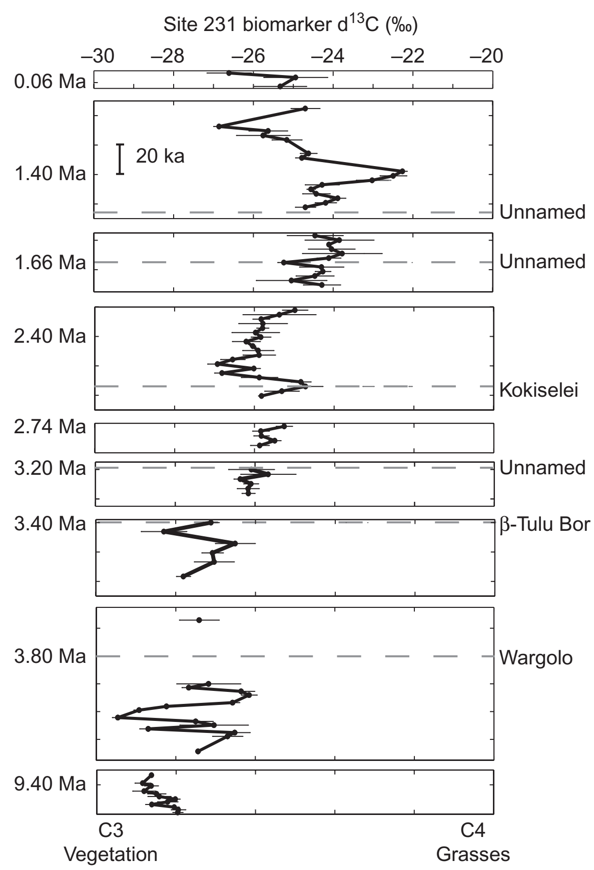

FIGURE 4.4 Carbon isotopic values of C_{30} *n*-alkanoic acids from DSDP Site 231 for nine 20- to 100-kyr time intervals spanning the late Neogene (near 9.4, 3.8, 3.4, 3.2, 2.7, 2.4, 1.7, 1.4, and 0.1 Ma; from Feakins et al., 2005). Mean $\delta^{13}C$ and 1σ analytical errors are shown. Vegetation changes are inferred based on $\delta^{13}C$ values of these C_{30} *n*-alkanoic acids, which have been identified as having a terrestrial vegetation source. Tephra age constraints are shown with dashed lines (Feakins et al., 2007). Foraminiferal $\delta^{18}O$ suggests interglacial timing of the upper interval rather than the glacial age (0.06 Ma) indicated by the interpolated age model.

It has been suggested that the mid-Miocene appearance of the C4 photosynthetic pathway may be linked to declining pCO_2 levels (Cerling et al., 1997b). However, alkenone-based pCO_2 reconstructions do not support this explanation and instead indicate that pCO_2 levels rose from a low of 180 ppm at 15 Ma, to 260–300 ppm between 8 and 6 Ma (Pagani et al., 1999). Alternatively, uplift of the Himalayas and resultant intensification of the Indian Monsoon (9–6 Ma; Molnar et al., 1993) may have altered the seasonality of precipitation in the region with increased aridity driving a shift to almost exclusively C4 vegetation in the summer precipitation regime in Pakistan (Quade and Cerling, 1995), and a mixed C3 and C4 vegetation in East Africa (Cerling et al., 1997b; Feakins et al., 2005; figure 4.4). Elsewhere, at Langebaanweg, South Africa, C3 vegetation remained dominant in the diet of grazing mammals at 5 Ma (Franz-Odendaal et al., 2002). Changing precipitation regimes (linked to regional circulation patterns; figure 4.2) would explain why C4 vegetation did not uniformly expand across Africa between 8 and 6 Ma and may also explain the late Pliocene and Pleistocene increase in C4 vegetation in East Africa (figure 4.4).

African environments also experienced cyclical precipitation variability during the late Neogene. Organic rich sapropel deposits in the Mediterranean indicate times of high runoff from the Nile catchment (Rossignol-Strick, 1985; Sachs and Repeta, 1999). These sapropel deposits occur at precessional minima indicating northeast African climate sensitivity to orbital variations in the seasonal distribution of insolation (Rossignol-Strick, 1985). Precessional frequency sapropel deposits are reported from at least 10 Ma onward (Hilgen, 1991; Hilgen et al., 1995; Krijgsman et al., 1995). Similarly, precessional cyclicity in terrigenous dust flux to marine sediments off West Africa is reported in the late Miocene indicating dramatic variability in dust availability in the source region or transport efficiency (Tiedemann et al., 1994; deMenocal, 1995; deMenocal and Bloemendal, 1995). These records suggest that precession provided the fundamental pacing of African humid-arid cycles during the Miocene.

A WARM AND WET MID-PLIOCENE

Global SST reconstructions indicate that the Pliocene included extended periods both warmer and cooler than today, with low-amplitude orbital frequency variability (Pliocene Research, Interpretation and Synoptic Mapping Project [PRISM]; Dowsett et al., 1996). Humid conditions leading up to the Pliocene are recorded in central and eastern North Africa during the Zeit Wet Phase (7.5–5.5 Ma) with an expanded Lake Chad and increased Nile runoff (Griffin, 2002). Even during the Messinian salinity crisis (6.7–5.33 Ma), when sea levels in the Mediterranean were minimal or completely dry, conditions in North Africa were wet (deMenocal and Bloemendal, 1995; Hilgen et al., 1995; Griffin, 1999).

The mid-Pliocene (4.5–3 Ma) was characterized by warmer conditions (+3°C) on average globally, higher sea levels (+10–20 m), reduced Antarctic ice cover, and percentage higher pCO_2 (Ravelo et al., 2004). The mid-Pliocene appears to have been broadly wetter throughout much of Africa consistent with PRISM model predictions in scenarios with increased meridional circulation and higher pCO_2 (Haywood and Valdes, 2004). For example, pollen records indicate that North Africa was wetter in the mid-Pliocene (Dupont and Leroy, 1995), and PRISM models predict that North Africa was warmer (by 5°C) and wetter (by 400–1,000 mm per year) relative to today (Haywood et al., 2000).

In the equatorial Pacific, the east to west SST gradient resembled a permanent El Niño, in contrast to the mean La Niña state in the modern ocean (Cannariato and Ravelo, 1997; Chaisson and Ravelo, 2000; Wara et al., 2005; Ravelo et al., 2006). Although the atmospheric teleconnection mechanisms associated with a modern El Niño event cannot simply be extrapolated to longer timescales, in many regions Pliocene climate appears to be roughly analogous to that observed in a modern El Niño (Molnar and Cane, 2002). In Africa, modern El Niño conditions are associated with anomalously wet conditions in East Africa and dry conditions in southeast Africa. We do find evidence for wet conditions in East Africa during the Pliocene, although it is hard to separate out the effects of warmer SSTs around Africa and teleconnections from the Pacific. Flora characteristic of the modern West African rain forest are found in East Africa around 3.4 Ma (Bonnefille and Letouzey, 1976; Bonnefille, 1987); soil carbonate records of vegetation in East and Central Africa indicate C3 vegetation and humid conditions (Cerling et al., 1977); lakes freshened in the Afar region of northeast Africa (Gasse, 1990), and Lake Tanganyika in southeast Africa expanded at about 3.6 Ma (Cohen et al., 1997). In southern Africa, there are fewer records, although vegetation appears to be relatively close to modern (Scott, 1995).

Most terrestrial records are at too low resolution to identify variability in the Pliocene. Marine records indicate that Pliocene African climate variability was dominated by precessional frequency (19–21 ka) variations in the strength of monsoonal precipitation. Precessional cycles in dust concentration (varying by a factor of 2–5) are seen in marine sediments off West and East Africa between 5 Ma and 2.8 Ma (figure 4.5), indicating dramatic variability in dust availability in the source region or transport efficiency (Tiedemann et al., 1994; deMenocal, 1995; deMenocal and Bloemendal, 1995). Evidence for precessionally driven precipitation changes in the Nile catchment in northeast Africa are seen in the organic-rich sapropel layers of the eastern Mediterranean throughout the Pliocene (Rossignol-Strick, 1983; Hilgen, 1991). Pollen from a terrestrial site at Hadar, Ethiopia, indicates an abrupt change in forest cover ca. 3.3 Ma (Bonnefille et al., 2004) that is consistent with environmental change during part of a precessional cycle identified in sapropel and dust records. Precessional variations in C3/C4 vegetation type are also seen in leaf wax biomarker records from marine sediments off northeast Africa ca. 3.8–3.7 Ma (figure 4.4; Feakins et al., 2005) and off southwest Africa ca. 2.56–2.51 Ma (Denison et al., 2005). These marine records clearly indicate that precession dominated the pacing of precipitation variations across Africa during the Pliocene.

PLIO-PLEISTOCENE ENVIRONMENTAL CHANGE

Major global climate events at the end of the Pliocene warm phase were not synchronous and instead occurred in a series of regional events (Ravelo et al., 2004). Tectonic processes caused significant reorganization of tropical ocean circulation during the late Pliocene. The restriction of the Panamanian seaway (4.5–4 Ma) caused changes in Atlantic circulation and an increase in meridional overturning (Haug and Tiedemann, 1998; Haug et al., 2001). The northward migration of New Guinea led to restriction of the Indonesian Seaway (4–3 Ma); models predict that this would likely have

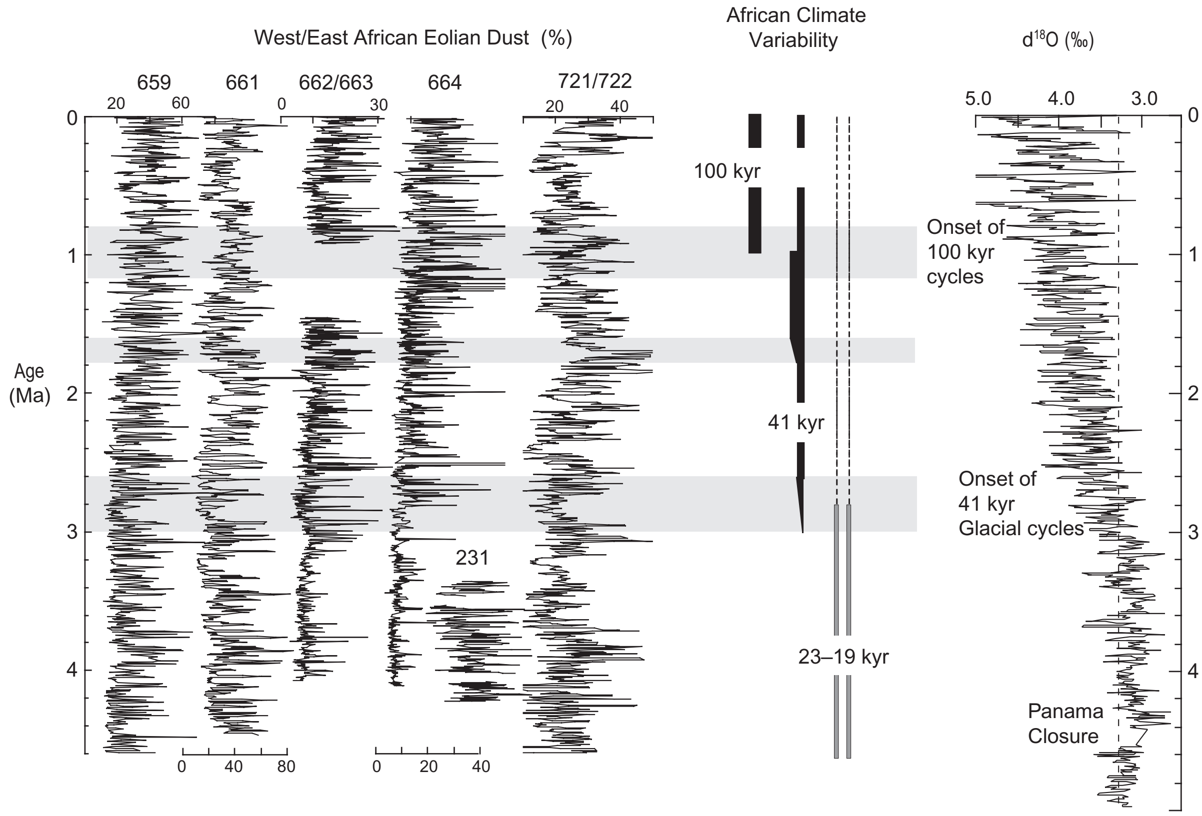

FIGURE 4.5 Pliocene-Pleistocene records of eolian dust deposition at seven DSDP/ODP sites off western and eastern subtropical Africa, together with summary indication of spectral analysis of those same dust records, and a stacked benthic oxygen isotope record. Reprinted with permission from deMenocal (2004). © 2004 Elsevier.

caused a cooling of Indian Ocean SSTs and a reduction of East African precipitation (Cane and Molnar, 2001). This predicted change in Indian Ocean SSTs is one possible explanation for the C4 vegetation expansion in East Africa after ca. 3.4 Ma seen in the leaf wax biomarker record (figure 4.4).

Significant Northern Hemisphere Glaciation began and intensified between 3.2 and 2.6 Ma (figure 4.1; Shackleton, 1995; Lisiecki and Raymo, 2005). Ocean temperatures cooled, and obliquity (41 ka) paced northern hemisphere glacial cycles commenced and intensified between 3.2 and 2.6 Ma (Shackleton, 1995; Lisiecki and Raymo, 2005). As the high latitudes cooled, most records indicate that Hadley circulation strengthened, trade winds intensified, and subtropical regions became more arid and more variable. Aridity and wind strength increased in North Africa at 2.8 ± 0.2 Ma as indicated by pollen (Dupont and Leroy, 1995) and dust records of West and East Africa (figure 4.5; Tiedemann et al., 1994; deMenocal, 1995; deMenocal and Bloemendal, 1995). In southern Africa, SSTs cooled with intensified upwelling, leading to greater aridity (Marlow et al., 2000). In contrast, lake levels in the Baringo-Bogoria Basin, Kenya, and Gadeb, Ethiopia, apparently record a wet interval from 2.7 to 2.5 Ma (Trauth et al., 2005, and references therein) indicating that perhaps not all of Africa experienced increased aridity at this time.

The onset of Northern Hemisphere glaciation signaled a change in the periodicity of some features of African climate variability. Dust records off West and East Africa document a shift from precession paced humid-arid cycles before 2.8 Ma, to obliquity frequency after ca. 2.8 Ma, suggesting a glacial control on either transport strength or source aridity (figure 4.5; deMenocal, 1995, 2004). Similarly, leaf wax biomarker records of southwest African vegetation document C3/C4 cycles in tune with obliquity paced Atlantic SST variations in the mid-Pleistocene (Schefuss et al., 2003), suggesting that glacial-interglacial cycles influenced African climate in both the Southern and Northern hemispheres.

Not all aspects of African climate were dominated by changes in the high latitudes, however. A second biomarker record from southwest Africa indicates that vegetation changes continued to be dominated by precessional timing shortly after the onset of Northern Hemisphere Glaciation (2.56–2.51 Ma; Denison et al., 2005). Precessional frequency precipitation variations are also recorded in the last 200 ka of the Pleistocene in Tswaing Impact Crater in South Africa (Partridge et al., 1997) and in various East African lakes (Trauth et al., 2001). Finally, sapropel stratigraphy indicates dominantly precessional timing of precipitation variations in northeast Africa throughout the Pliocene and Pleistocene (Rossignol-Strick, 1983; Tuenter et al., 2003). Therefore, despite evidence that Northern Hemisphere glacial cycles led African aridity, there are many counterindications of independent precessional pacing of African climate, particularly in those proxies that directly relate to precipitation.

The tropical Pacific was also partially decoupled from high-latitude climate. Despite significant high-latitude changes ca. 2.8 Ma, tropical Pacific SST gradients appeared to have remained largely stable with El Niño–like conditions until ca. 2 Ma (Chaisson and Ravelo, 2000; Wara et al., 2005; Ravelo et al., 2006). The reorganization of the tropical Pacific ca. 2 Ma occurred at a time when high-latitude climate was relatively invariant (Wara et al., 2005). A cooling of eastern Pacific SSTs ca. 2 Ma relative to warm SSTs in the western Pacific (La Niña–like conditions) indicates the initiation of Walker circulation and the likely beginning of ENSO variability.

This reorganization of the tropical Pacific, from an El Niño–like to a La Niña–like mean state, may have produced climate repercussions with a global signature, since the same mechanisms that generate interannual ENSO variability in modern climates may also produce variability on longer timescales (Cane and Zebiak, 1985; Clement et al., 2001; Molnar and Cane, 2002). Around this time, biostratigraphic events mark the Plio-Pleistocene boundary and local cooling in the Mediterranean (1.77 Ma; Raffi et al., 1993), and an increase in dust flux off Africa records increased aridity (deMenocal, 1995). A C4 expansion is seen in the Turkana Basin, East Africa (2–1.7 Ma; Cerling et al., 1977), and organic carbon concentrations dramatically increase in marine sediments off West Africa (2.45–1.7 Ma; Wagner, 2002). These records appear to indicate an arid shift in North African climate ca. 2 Ma coincident with a major reorganization of the tropical ocean-atmosphere system to a mean La Niña–like mean state.

COOL AND DRY CONDITIONS DURING THE LAST GLACIAL MAXIMUM

Most terrestrial paleoclimate research for Africa has focused on the Last Glacial Maximum (LGM) to the present, for which the geomorphological evidence is typically best preserved and reconstructions are within the range of radiocarbon and optical dating. Tropical paleoclimate records for the LGM have been reconsidered since CLIMAP concluded that there was minimal cooling (<2°C) or even a slight warming in the tropics (CLIMAP-project, 1976). Tropical SST reconstructions from the Atlantic (Guilderson et al., 1994; Emiliani, 1995; Lea et al., 2003), Indian (Sonzogni et al., 1998; Visser et al., 2003), and Pacific oceans (Emiliani, 1995; Prahl et al., 1995) have now demonstrated a 2°–6°C glacial cooling relative to modern. In addition, many modeling studies support the evidence for cooler tropical temperatures during glacials (Rind and Peteet, 1985; Pinot et al., 1999). Terrestrial temperature reconstructions also indicate significant cooling at the LGM. In East Africa cooling estimates include 5°–6°C from tropical snowline depressions (Rind and Peteet, 1985), 2°–8°C from pollen assemblages (Coetzee, 1967; Chalie, 1995), and 3°–5°C in Lake Malawi from the new TEX_{86} molecular paleothermometer (Powers et al., 2005). In South Africa, 5°C glacial cooling is estimated from speleothems (Talma and Vogel, 1992; Holmgren et al., 2003) and groundwater (Kulongoski et al., 2004).

However, aridity changes may be more critical than temperature changes for flora and fauna in African environments. Modern climate patterns would predict reduced precipitation in most regions as a result of cooler glacial SSTs. Various terrestrial records indicate broad arid phases between 23 and 17 ka during the LGM. Fossil sand dunes indicate that the Sahara expanded southward during the LGM (Grove and Warren, 1968; Mauz and Felix-Henningsen, 2005). Terrigenous dust (Tiedemann et al., 1994; deMenocal, 1995), pollen (Dupont and Leroy, 1995; Hooghiemstra et al., 1998), and leaf wax biomarkers (Zhao et al., 2003) transported to marine sediments off northwest Africa indicate increased aridity and trade wind strength during the last glacial. Other terrigenous material reaching marine sediments include *Melosira,* freshwater diatoms, deflated from dry West African lake beds during the LGM (Pokras and Mix, 1987), and grass phytoliths that indicate increased aridity in cold stages (Abrantes, 2003). Lake levels were almost uniformly low across Africa (Street and Grove, 1979). Leaf wax biomarker hydrogen isotope reconstructions from the Congo fan record arid conditions in Central Africa (Schefuss et al., 2005). In southern Africa, fossil dunes in the Mega Kalahari (Stokes et al., 1997) and sedimentation in the Tswaing Impact Crater (Partridge et al., 1997) indicate arid conditions 26–10 ka. In East Africa, Lakes Victoria (Talbot and Laerdal, 2000) and Albert (Beuning et al., 1997) record two prolonged droughts between 18 and 12.5 ^{14}C ka that led to complete desiccation of both lakes. Lake levels in Lake Tanganyika dropped by ~350 m (Scholz et al., 2003). A diatom record from Lake Massoko, Tanzania, shares the pattern of climate variability seen in the northeast African lakes with dry conditions up to 15 ka (Barker et al., 2003). Pollen-based precipitation reconstructions from Burundi also indicate an arid LGM (Bonnefille and Chalie, 2000). These precipitation records correlate well with alkenone-derived SST reconstructions in the southwest Indian Ocean (Sonzogni et al., 1998), suggesting that cool SSTs resulted in reduced East African precipitation during the LGM. These many records indicate arid conditions throughout much of Africa at the LGM.

THE HOLOCENE

The early Holocene was anomalously wet in most of Africa. Lake levels across Africa are almost uniformly higher and indicate a 150- to 400-mm annual increase in precipitation in the Sahara (Street and Grove, 1979; Street-Perrott and Harrison, 1984). Fluvial sediments, lacustrine carbonates, freshwater algae, faunal records, paleosols, and stabilized fossil dunes all indicate that the early to mid-Holocene was more humid than the present (e.g., Haynes and Mead, 1987; Kropelin and Soulie-Marsche, 1991). Marine records off West Africa indicate that the "African Humid Period" extended from 15 to 5 ka in North Africa (Pokras and Mix, 1987; deMenocal et al., 2000). While records from South Africa are comparatively rare, stalagmites in Makapansgat Valley and pollen records from Wonderkrater have revealed generally warm conditions between 10 and 6 ka (Scott, 1999; Holmgren et al., 2003).

High-resolution paleoclimate records are revealing new details of Holocene climate change. A tropical ice core, recovered from Mount Kilimanjaro, Tanzania, has provided a continuous and detailed record of East African climate variability throughout the entire Holocene (Thompson et al., 2002). The ice core oxygen isotope and aerosol records indicate an abrupt cooling and drying event ca. 8.3 ka that corresponds to a cooling event in the North Atlantic Ocean (Alley et al., 1997). Further arid shifts are observed between 6.4 and 5.2 ka and at 4 ka (Thompson et al., 2002).

The late Holocene has been comparatively arid in much of Africa. An abrupt transition has been identified in many tropical records ca. 4 ka (Marchant and Hooghiemstra, 2004). Late Holocene arid conditions in East Africa are recorded in Arabian Sea dust records (Davies et al., 2002) and lake-level low stands (Halfman and Johnson, 1988; Talbot and Laerdal, 2000). In West Africa, there is evidence for a southerly shift of arid vegetation zones (Kutzbach and Street-Perrot, 1985; Lezine, 1989) and low lake levels since mid-Holocene times (Street and Grove, 1979; Street-Perrott and Perrott, 1990). This mid-Holocene transition to arid conditions in Africa is largely independent of high-latitude climate change (Marchant and Hooghiemstra, 2004). Modeling studies suggest that this humid-arid transition is strongly dependent on a nonlinear climate response to precessional insolation forcing (Claussen et al., 1999). Thus in the Holocene, like much of the late Neogene, we find evidence for precessional forcing of African climate change.

Literature Cited

Abrantes, F. 2003. A 340,000 year continental climate record from tropical Africa: News from opal phytoliths from the equatorial Atlantic. *Earth and Planetary Science Letters* 209:165–179.

Alley, R. B., P. A. Mayewski, T. Sowers, M. Stuiver, K. C. Taylor, and P. U. Clark. 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25:483–486.

Anka, Z., and M. Séranne. 2004. Reconnaissance study of the ancient Zaire (Congo) deep-sea fan (ZaiAngo Project). *Marine Geology* 209:223–244.

Barker, P., D. Williamson, F. Gasse, and E. Gibert. 2003. Climatic and volcanic forcing revealed in a 50,000-year diatom record from Lake Massoko, Tanzania. *Quaternary Research* 60:368–376.

Beuning, K. R. M., M. R. Talbot, and K. Kelts. 1997. A revised 30,000-year paleoclimatic and paleohydrologic history of Lake Albert, East Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 136:259–279.

Bolle, M. P., T. Adatte, G. Keller, K. Von Salis, and S. Burns. 1999. The Paleocene-Eocene transition in the southern Tethys (Tunisia): Climatic and environmental fluctuations. *Bulletin de la Société Géologique de France* 170:661–680.

Bonnefille, R. 1987. Forest and climatic history during the last 40,000 yrs in Burundi. *Comptes Rendus de l'Académie des Sciences,* Série II, 305:1021–1026.

Bonnefille, R., and F. Chalie. 2000. Pollen-inferred precipitation time-series from equatorial mountains, Africa, the last 40 kyr BP. *Global and Planetary Change* 26:25–50.

Bonnefille, R., and R. Letouzey. 1976. Fruits fossiles d'*Antrocaryon* dans la vallée de l'Omo (Ethiopie). *Adansonia* 16:65–82.

Bonnefille, R., R. Potts, F. Chalie, D. Jolly, and O. Peyron. 2004. High-resolution vegetation and climate change associated with Pliocene *Australopithecus afarensis*. *Proceedings of the National Academy of Sciences, USA* 101:12125–12129.

Camberlin, P., S. Janicot, and I. Poccard. 2001. Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. *International Journal of Climatology* 21:973–1005.

Cane, M., and A. C. Clement. 1999. A role for the tropical Pacific coupled ocean-atmosphere system on Milankovitch and millennial timescales. Part II: Global impacts; pp. 373–383 in P. Clark, R. S. Webb, and L. D. Keigwin (eds.), *Mechanisms of Global Climate Change at Millennial Time Scales*. American Geophysical Union, Washington, D.C.

Cane, M. A., G. Eshel, and R. Buckland. 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature* 370:204–206.

Cane, M. A., and P. Molnar. 2001. Closing of the Indonesian Seaway as the missing link between Pliocene East African aridification and the Pacific. *Nature* 411:157–162.

Cane, M. A., and S. Zebiak. 1985. A theory for El Niño and the Southern Oscillation. *Science* 228:1085–1087.

Cannariato, K. G., and A. C. Ravelo. 1997. Pliocene-Pleistocene evolution of eastern tropical Pacific surface water circulation and thermocline depth. *Paleoceanography* 12:805–820.

Cerling, T. E., J. M. Harris, S. H. Ambrose, M. G. Leakey, and N. Solounias. 1997a. Dietary and environmental reconstruction with stable isotope analyses of herbivore tooth enamel from the Miocene locality of Fort Ternan, Kenya. *Journal of Human Evolution* 33:635–650.

Cerling, T. E., J. M. Harris, B. J. MacFadden, M. G. Leakey, J. Quade, V. Eisenmann, and J. R. Ehleringer. 1997b. Global vegetation change through the Miocene/Pliocene boundary. *Nature* 389:153–158.

Cerling, T. E., R. L. Hay, and J. R. O'Neil. 1977. Isotopic evidence for dramatic climatic changes in East-Africa during Pleistocene. *Nature* 267:137–138.

Chaisson, W. P., and A. C. Ravelo. 2000. Pliocene development of the east-west hydrographic gradient in the equatorial Pacific. *Paleoceanography* 15:497–505.

Chalie, F. 1995. Paleoclimates of the southern Tanganyika Basin over the last 25-thousand years: Quantitative reconstruction from the statistical treatment of pollen data. *Comptes Rendus de l'Académie des Sciences,* Série II, 320:205–210.

Claussen, M., C. Kubatzki, V. Brovkin, A. Ganapolski, P. Hoelzmann, and H.-J. Pachur. 1999. Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. *Geophysical Research Letters* 26:2037–2040.

Clement, A. C., M. A. Cane, and R. Seager. 2001. An orbitally driven tropical source for abrupt climate change. *Journal of Climate* 14:2369–2375.

CLIMAP-project. 1976. The surface of the ice-age Earth. *Science* 191:1131–1136.

Coetzee, J. 1967. Pollen analytical studies in East and southern Africa. *Paleoecology of Africa* 3:1–46.

Cohen, A., K. E. Lezzar, J. J. Tiercelin, and M. Soreghan. 1997. New palaeogeographic and lake-level reconstructions of Lake Tanganyika: Implications for tectonic, climatic and biological evolution in a rift lake. *Basin Research* 9:107–132.

Dansgaard, W. S., S. Johnsen, H. B. Glausen, D. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C. S. Hvidberg, J. Steffesen, A. E. Sveinsbjörnsdottir, J. Jouzel, and G. Bond. 1993. Evidence for general instability of past climate from a 250-kyr ice core record. *Nature* 364:218–220.

Davies, G. R., S. J. A. Jung, and G. M. Ganssen. 2002. Abrupt climate change in N-Africa: The asynchronous termination of the African Humid Period. *Geochimica et Cosmochimica Acta* 66(15A):A170–A170.

deMenocal, P. B. 1995. Plio-Pleistocene African climate. *Science* 270:53–59.

———. 2004. African climate change and faunal evolution during the Pliocene-Pleistocene. *Earth and Planetary Science Letters* 220:3–24.

deMenocal, P., and J. Bloemendal. 1995. Plio-Pleistocene climatic variability in subtropical Africa and the paleoenvironment of hominid evolution: A combined data-model approach; pp. 262–288 in E. Vrba, G. Denton, T. Partridge, and L. Burckle (eds.), *Paleoclimate and Evolution: With Emphasis on Human Origins*. Yale University Press, New Haven.

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

Denison, S., M. A. Maslin, C. Boot, R. Pancost, and V. Ettwein. 2005. Precession-forced changes in South West African vegetation during Marine Isotope Stages 101–100 (~2.56–2.51 Ma). *Palaeogeography Palaeoclimatology Palaeoecology* 220:375–386.

Denton, G. H. 1999. Cenozoic climate change; pp. 94–114 in T. Bromage and F. Schrenk (eds.), *African Biogeography, Climate Change and Human Evolution*. Oxford University Press, Oxford.

Diester-Haass, L., P. Meyers, and P. Rothe. 1990. Miocene history of the Benguela current and Antarctic ice volumes: evidence from rhythmic sedimentation and current growth across the Walvis Ridge (DSDP Sites 362 and 532). *Paleoceanography* 5:685–707.

Dowsett, H., J. Barron, and R. Z. Poore. 1996. Middle Pliocene sea-surface temperatures: A global reconstruction. *Marine Micropaleontology* 27:13–25.

Dupont, L., and S. Leroy. 1995. Steps towards drier climatic conditions in Northwestern Africa during the Upper Pliocene; pp. 289–297 in E. Vrba, G. Denton, T. Partridge, and L. Burckle (eds.), *Paleoclimate and Evolution: With Emphasis on Human Origins*. Yale University Press, New Haven.

Emiliani, C. 1995. Tropical paleotemperatures. *Science* 268:1264.

Feakins, S. J., F. H. Brown, and P. B. deMenocal. 2007. Plio-Pleistocene Microtephra in DSDP Site 231, Gulf of Aden. *Journal of African Earth Sciences* 48:341–352

Feakins, S. J., P. B. deMenocal, and T. I. Eglinton. 2005. Biomarker records of Late Neogene changes in East African vegetation. *Geology* 33:977–980.

Franz-Odendaal, T. A., J. A. Lee-Thorp, and A. Chinsamy. 2002. New evidence for the lack of C-4 grassland expansions during the early Pliocene at Langebaanweg, South Africa. *Paleobiology* 28:378–388.

Gasse, F. 1990. Tectonic and climatic controls on lake distribution and environments in Afar from Miocene to Present; pp. 19–41 in B. Katz (ed.), *Lacustrine Basin Exploration: Case Studies and Modern Analogs*. Memoirs of the American Association of Petroleum Geologists, 50.

Giannini, A., R. Saravan, and P. Chang. 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302:1027–1030.
Gingerich, P. D. 2004. Paleogene vertebrates and their response to environmental change. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 234:1–23.
Goddard, L., and N. E. Graham. 1999. Importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. *Journal of Geophysical Research* 104:19,099–19,116.
Griffin, D. L. 1999. The late Miocene climate of northeastern Africa: Unravelling the signals in the sedimentary succession. *Journal of the Geological Society, London* 156:817–826.
———. 2002. Aridity and humidity: Two aspects of the late Miocene climate of North Africa and the Mediterranean. *Paleogeography, Paleoclimatology, Paleoecology* 182:65–91.
Grove, A. T., and A. Warren. 1968. Quaternary landforms and climate on the south side of the Sahara. *Geographical Journal* 134:194–208.
Guilderson, T. P., R. P. Fairbanks, and J. L. Rubenstone. 1994. Tropical temperature variations since 20,000 years ago: modulating interhemispheric climate change. *Science* 263:663–665.
Guiraud, R. 1978. Le Continental Intercalaire en Algérie. *Annales de la Faculte des Sciences de Dakar* 31:85–87.
Halfman, J., and T. Johnson. 1988. High-resolution record of cyclic climatic change during the past 4 ka from Lake Turkana, Kenya. *Geology* 16:496–500.
Hastenrath, S., A. Nicklis, and L. Greischar. 1993. Atmospheric-hydrospheric mechanisms of climate anomalies in the western equatorial Indian Ocean. *Journal of Geophysical Research* 98:219–235.
Haug, G. H., and R. Tiedemann. 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. *Nature* 393:673–676.
Haug, G. H., R. Tiedemann, R. Zahn, and A. C. Ravelo. 2001. Role of Panama uplift on oceanic freshwater balance. *Geology* 29:207–210.
Haynes, C. V., and A. R. Mead. 1987. Radiocarbon dating and paleoclimatic significance of sub-fossil *Limicolaria* in NW Sudan. *Quaternary Research* 28:86–89.
Haywood, A., B. Sellwood, and P. Valdes. 2000. Regional warming: Pliocene (3Ma) paleoclimate of Europe and Mediterranean. *Geology* 38:1063–1066.
Haywood, A., and P. Valdes. 2004. Modelling Pliocene warmth: Contribution of atmosphere, oceans and cryosphere. *Earth and Planetary Science Letters* 218:363–377.
Hilgen, F. J. 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the geomagnetic polarity time scale. *Earth and Planetary Science Letters* 104:226–244.
Hilgen, F., W. Krijgsman, C. Langereis, L. J. Lourens, A. Santarelli, and W. J. Zachariasse. 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth and Planetary Science Letters* 136:495–510.
Hoerling, M. P., J. W. Hurrell, and T. Xu. 2001. Tropical origins for recent North Atlantic climate change. *Science* 292:90–92.
Holmgren, K., J. Lee-Thorp, G. Cooper, K. Lundblad, T. C. Partridge, L. Scott, R. Sithaldeen, A. Talma, and P. Tyson. 2003. Persistent millennial-scale climatic variability over the past 25,000 years in Southern Africa. *Quaternary Science Reviews* 22:2311–2326.
Hooghiemstra, H., R. Bonnefille, and H. Behling. 1998. Intertropical last glacial and Holocene climatic change. *Review of Palaeobotany and Palynology* 99:75–76.
Hurrell, J. W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* 269:676–679.
Jacobs, B. F. and P. Herendeen. 2004. Eocene dry climate and woodland vegetation in tropical Africa reconstructed from fossil leaves from northern Tanzania. *Palaeogeography, Palaeoclimatology, Palaeoecology* 213:115–123.
Janowiak, J. 1988. An investigation of interannual rainfall variability in Africa. *Journal of Climate* 1:240–255.
Kennett, J. P. 1995. A review of polar climatic evolution during the Neogene, based on the marine sediment record; pp. 49–64 in E. Vrba, G. Denton, T. Partridge, and L. Burckle (eds.), *Paleoclimate and Evolution: With Emphasis on Human Origins*. Yale University Press, New Haven.
Kingston, J., B. F. Jacobs, A. Hill, and A. Deino. 2002. Stratigraphy, age and environments of the late Miocene Mpesida Beds, Tugen Hills, Kenya. *Journal of Human Evolution* 42:92–116.
Knippertz, P., U. Ulbrich, F. Marques, and J. Corte-Real. 2003. Decadal changes in the link between El Niño and springtime North Atlantic oscillation and European–North African rainfall. *International Journal of Climatology* 23:1293–1311.
Kobashi, T., E. L. Grossman, T. E. Yancey, and D. T. Dockery III. 2001. Reevaluation of conflicting Eocene tropical temperature estimates: Molluscan oxygen isotope evidence for warm low latitudes. *Geology* 29:983–986.
Krijgsman, W., F. Hilgen, C. Langereis, A. Santarelli, and W. Zachariasse. 1995. Late Miocene magnetostratigraphy, biostratigraphy and cyclostratigraphy in the Mediterranean. *Earth and Planetary Science Letters* 136:475–494.
Kropelin, S., and I. Soulie-Marsche. 1991. Charophyte remains from Wadi Howar as evidence for deep mid-Holocene freshwater lakes in the eastern Sahara of northwest Sudan. *Quaternary Research* 36:210–223.
Kulongoski, J., D. Hilton, and E. Selaolo. 2004. Climate variability in the Kotswana Kalahari from the late Pleistocene to the present day. *Geophysical Research Letters* 31:L10204. doi:10.1029/2003GL019238.
Kutzbach, J. E., and F. A. Street-Perrot. 1985. Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP. *Nature* 317:130–134.
Lea, D. W., D. Pak, L. Peterson, and K. Hughen. 2003. Synchroneity of tropical and high-latitude Atlantic temperatures over the last glacial termination. *Science* 301:1361–1364.
Leakey, M. G., C. S. Feibel, R. L. Bernor, J. M. Harris, T. E. Cerling, K. M. Stewart, G. W. Storrs, A. Walker, L. Werdelin, and A. J. Winkler. 1996. Lothagam: A record of faunal change in the late Miocene of East Africa. *Journal of Vertebrate Paleontology* 16:556–570.
Le Houerou, H. 1997. Climate, flora and fauna changes in the Sahara over the past 500 million years. *Journal of Arid Environments* 37:619–647.
Lezine, A. M. 1989. Late Quaternary vegetation and climate of the Sahel. *Quaternary Research* 32:317–334.
Linsley, B. K., G. Wellington, and D. P. Schrag. 2000. Decadal sea surface temperature variability in the subtropical south Pacific from 1726–1997 AD. *Science* 290:1145–1148.
Lisiecki, L., and M. Raymo. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* 20:1–17.
Liu, Z., B. Otto-Bleisner, J. Kutzbach, L. Li, and C. Shields. 2003. Coupled climate simulation of the evolution of global monsoons in the Holocene. *Journal of Climate* 16:2472–2490.
Marchant, R., and H. Hooghiemstra. 2004. Rapid environmental change in African and South American tropics around 4000 years before present: A review. *Earth-Science Reviews* 66:217–260.
Marlow, J. R., C. B. Lange, G. Wefer, and A. Rosell-Melé. 2000. Upwelling intensification as a part of the Pliocene-Pleistocene climate transition. *Science* 290:2288–2291.
Mauz, B., and P. Felix-Henningsen. 2005. Palaeosols in Saharan and Sahelian dunes of Chad: Archives of Holocene North African climate changes. *The Holocene* 15:453–458.
Molnar, P., and M. A. Cane. 2002. El Niño's tropical climate and teleconnections as a blueprint for pre-Ice Age climates. *Paleoceanography* 17:1021. doi:10.1029/2001PA000663.
Molnar, P., P. England, and J. Martinod. 1993. Mantle dynamics, uplift of the Tibetan Plateau and the Indian Monsoon. *Reviews of Geophysics* 31:357–396.
Nicholson, S. 2000. The nature of rainfall variability over African on time scales of decades to millennia. *Global and Planetary Change* 26:137–158.
Nicholson, S., and D. Entekhabi. 1987. Rainfall variability in equatorial and southern Africa: Relationships with sea surface temperatures along the southwestern coast of Africa. *Journal of Applied Meteorology* 26:561–578.
Pagani, M., M. Arthur, and K. H. Freeman. 1999. Miocene evolution of atmospheric carbon dioxide. *Paleoceanography* 14:273–292.
Partridge, T., P. B. deMenocal, S. Lorentz, M. Paiker, and J. Vogel. 1997. Orbital forcing of climate over South Africa: A 200,000-year rainfall record from the Pretoria Saltpan. *Quaternary Science Reviews* 16:1125–1133.
Pearson, P., P. Ditchfield, J. Singano, K. Harcourt-Brown, C. Nicholas, R. Olsson, N. J. Shackleton, and M. Hall. 2001. Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs. *Nature* 413:481–487.
Pearson, P., and M. Palmer. 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature* 406:695–699.
Pinot, S., G. Ramstein, S. P. Harrison, I. C. Prentice, J. Guiot, M. Stute, and S. Joussaume. 1999. Tropical paleoclimates at the Last Glacial

Maximum: Comparison of Paleoclimate Modeling Intercomparison Project (PMIP) simulations and paleodata. *Climate Dynamics* 15:857–874.

Pokras, E., and A. C. Mix. 1987. Earth's precession cycle and Quaternary climatic change in tropical Africa. *Nature* 326:486–487.

Powers, L., T. Johnson, J. Werne, I. Castaneda, E. Hopmans, J. S. Damsté, and S. Schouten. 2005. Large temperature variability in the southern African tropics since the Last Glacial Maximum. *Geophysical Research Letters* 32 doi:10.1029/ 2004GL02214.

Prahl, F., N. Pisias, M. Sparrow, and A. Sabin. 1995. Assessment of sea surface temperature at 42°N in the California current over the last 30 000 years. *Paleoceanography* 4:763–773.

Quade, J. and T. E. Cerling. 1995. Expansion of C-4 grasses in the Late Miocene of Northern Pakistan: Evidence from Stable Isotopes in Paleosols. *Palaeogeography, Palaeoclimatology, Palaeoecology* 115:91–116.

Raffi, I., J. Backman, D. Rio, and N. J. Shackleton. 1993. Plio-Pleistocene nannofossil biostratigraphy and calibration to oxygen isotope stratigraphies from DSDP site 607 ODP site 677. *Paleoceanography* 8:387–408.

Ravelo, A. C., P. S. Dekens, and M. McCarthy. 2006. Evidence for El Niño–like conditions during the Pliocene. *GSA Today* 16:4–11. doi: 10.1130/1052-5173.

Ravelo, A., D. Andreasen, M. Lyle, A. Olivarez-Lyle, and M. Wara. 2004. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. *Nature* 429:263–267.

Retallack, G. J. 1992. Middle Miocene fossil plants from Fort Ternan (Kenya) and evolution of African grasslands. *Paleobiology* 18:383–400.

Rind, D. and D. Peteet. 1985. Terrestrial conditions at the last glacial maximum and CLIMAP sea-surface temperature estimates: Are they consistent? *Quaternary Research* 24:1–22.

Robert, C., L. Diester-Haass, and J. Paturel. 2005. Clay mineral assemblages, siliciclastic input and paleoproductivity at ODP Site 1085 off Southwest Africa: A late Miocene–early Pliocene history of Orange river discharges and Benguela current activity, and their relation to global sea level change. *Marine Geology* 216:221–238.

Rodwell, M., and B. Hoskins. 1996. Monsoons and the dynamics of deserts. *Quarterly Journal of the Royal Meteorological Society* 122:1385–1404.

Ropelewski, C., and M. Halpert. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review* 115:1606–1627.

Rossignol-Strick, M. 1983. African monsoons, an immediate climatic response to orbital insolation forcing. *Nature* 304:46–49.

———. 1985. Mediterranean Quaternary sapropels, an immediate response of the African Monsoon to variation of insolation. *Palaeogeography Palaeoclimatology Palaeoecology* 49:237–263.

Rowell, D., C. Folland, K. Maskell, and M. Ward. 1995. Variability of summer rainfall over tropical north Africa (1906–92): Observations and modelling. *Quarterly Journal of the Royal Meteorological Society* 121:669–704.

Sachs, J. P., and D. J. Repeta. 1999. Oligotrophy and nitrogen fixation during eastern Mediterranean sapropel events. *Science* 286:2485–2488.

Schefuss, E., S. Schouten, J. H. F. Jansen, and J. S. S. Damsté. 2003. African vegetation controlled by tropical sea surface temperatures in the mid-Pleistocene period. *Nature* 422:418–421.

Schefuss, E., S. Schouten, and R. Schneider. 2005. Climatic controls on central African hydrology during the past 20,000 years. *Nature* 437:1003–1006.

Scholz, C., J. King, G. Ellis, P. Swart, J. C. Stager, and S. Colman. 2003. Paleolimnology of Lake Tanganyika, East Africa over the past 100 kyr. *Journal of Paleolimnology* 30:139–150.

Scott, L. 1995. Pollen evidence for vegetational and climatic change in southern Africa during the Neogene and Quaternary; pp. 65–76 in E. Vrba, G. Denton, T. Partridge, and L. Burckle (eds.), *Paleoclimate and Evolution: With Emphasis on Human Origins*. Yale University Press, New Haven.

———. 1999. The vegetation history and climate in the Savanna Biome, South Africa since 190 ka: A comparison of pollen data from the Tswaing Crater (the Pretoria Saltpan) and Wonderkrater. *Quaternary International* 57:215–223.

Semazzi, F., V. Mehta, and Y. Sud. 1988. An investigation of the relationship between sub-Saharan rainfall and global sea surface temperatures. *Atmosphere-Oc*ean 26:118–138.

Shackleton, N. 1995. New data on the evolution of Pliocene climatic variability; pp. 242–248 in E. Vrba (eds.), *Paleoclimate and Evolution: With Emphasis on Human Origins*. Yale University Press, New Haven.

Sonzogni, C., E. Bard, and F. Rostek. 1998. Tropical sea surface temperature during the last glacial period: A view based on alkenones in Indian ocean sediments. *Quaternary Science Reviews* 17:1185–1201.

Stokes, S., D. S. G. Thomas, and R. Washington. 1997. Multiple episodes of aridity in southern Africa since the last interglacial period. *Nature* 388:154–158.

Stott, L., and J. P. Kennett. 1990. Antarctic Paleogene planktonic foraminifer biostratigraphy, ODP Leg 113, Sites 689 and 690. *Proceedings of the Ocean Drilling Program, Scientific Results* 113:549–569.

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

Street-Perrott, F. A., and S. A. Harrison. 1984. Temporal variations in lake levels since 30,000 yr BP: An index of the global hydrological cycle; pp. 118–129 in J. E. Hansen and T. Takahashi (eds.), *Climate Processes and Climate Sensitivity*. American Geophysical Union, Washington, D.C.

Street-Perrott, F., and R. A. Perrott. 1990. Abrupt climate fluctuations in the tropics: The influence of Atlantic Ocean circulation. *Nature* 343:607–612.

Talbot, M., and T. Laerdal. 2000. The Late Pleistocene–Holocene palaeolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary organic matter. *Journal of Paleolimnology* 23:141–164.

Talma, A. S., and J. C. Vogel. 1992. Late Quaternary palaeotemperatures derived from a speleothem from Cango Caves, Cape Province, South Africa. *Quaternary Research* 37:203–213.

Thompson, L., E. Mosley-Thompson, M. Davis, K. Henderson, H. Brecher, V. Zagorodnov, T. Mashiotta, L. Ping-Nan, V. Mikhalenko, D. Hardy, and J. Beer. 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* 298:589–593.

Tiedemann, R., M. Sarnthein, and N. J. Shackleton. 1994. Astronomical timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of ODP Site 659. *Paleoceanography* 9:619–638.

Trauth, M., A. Deino, and M. Strecker. 2001. Response of the East African climate to orbital forcing during the last interglacial (130–117 ka) and the early last glacial (117–60 ka). *Geology* 29:499–502.

Trauth, M., M. A. Maslin, A. Deino, and M. Strecker. 2005. Late Cenozoic moisture history of East Africa. *Science* 5743:2052–2053.

Trenberth, K., W. Branstator, D. Karoly, A. Kumar, N. Lau, and C. Ropelewski. 1998. Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *Journal of Geophysical Research* 103:14291–14324.

Tuenter, E., S. Weber, F. Hilgen, and L. Lourens. 2003. The response of the African summer monsoon to remote and local forcing due to precession and obliquity. *Global and Planetary Change* 36:219–235.

Visser, K., R. Thunell, and L. Stott. 2003. Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation. *Nature* 421:152–155.

Wagner, T. 2002. Late Cretaceous to early Quaternary organic sedimentation in the eastern Equatorial Atlantic. *Palaeogeography Palaeoclimatology Palaeoecology* 179:113–147.

Wara, M., A. C. Ravelo, and M. Delaney. 2005. Permanent El Niño–like conditions during the Pliocene Warm Period. *Science* 309:758–761.

Wynn, J. G. 2004. Influence of Plio-Pleistocene aridification on human evolution: Evidence from paleosols of the Turkana Basin, Kenya. *American Journal of Physical Anthropology* 123:106–118.

Yemane, K., C. Robert, and R. Bonnefille. 1987. Pollen and clay mineral assemblages of a late Miocene lacustrine sequence from the northwestern Ethiopian highlands. *Palaeogeography Palaeoclimatology Palaeoecology* 60:123–141.

Yin, J., and D. Battisti. 2001. The importance of tropical sea surface temperature patterns in simulations of last glacial maximum climate. *Journal of Climate* 14:565–581.

Zachos, J. C., L. Stott, and K. Lohmann. 1994. Evolution of early Cenozoic marine temperatures. *Paleoceanography* 9:353–387.

Zachos, J. C., M. Pagani, L. Sloan, E. Thomas, and K. Billups. 2001. Trends, rhythms and aberrations in global climate 65 Ma to Present. *Science* 292:686–692.

Zhao, M. X., L. Dupont, G. Eglinton, and M. Teece. 2003. n-alkane and pollen reconstruction of terrestrial climate and vegetation for NW Africa over the last 160 kyr. *Organic Geochemistry* 34:131–143.