Tying celestial mechanics to Earth's ice ages

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Uganda's Margherita glacier, in the Rwenzori Mountains, provides the Nile River with some of its water. (Morgan Trimble/Alamy Stock Photo.)

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Gradual falls and sharp rises in temperature for millions of years have profoundly affected living conditions on the planet and, consequently, our own evolution.

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Milutin Milanković, a brilliant Serbian mathematician and climatologist, postulated in 1941 that variations in Earth's orbit could push the planet's climate in or out of an ice age.[1] Vital to that idea is the amount of insolation—incoming solar radiation—at 65°N, a bit south of the Arctic Circle. At that latitude, insolation can vary seasonally by 25%. Milanković argued that reductions in summer insolation allow some winter ice to survive. Each year for thousands of years, ice accumulates around 65°N and eventually forms sheets large enough to trigger an ice age.

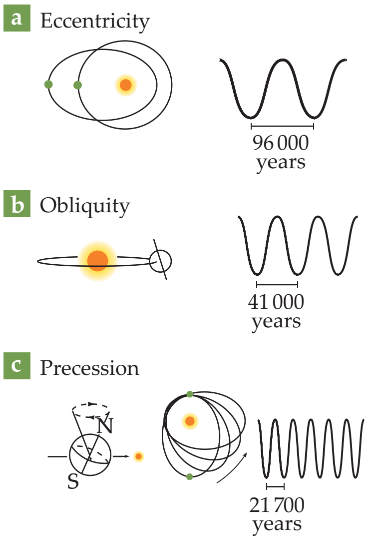


FIGURE 1. MILANKOVITCH CYCLES comprise three types of variation in Earth's motion. Eccentricity **(a)** describes the shape of Earth's orbit around the Sun, which varies from nearly circular to more elliptical with a period of about 96 000 years. Obliquity **(b)** is the tilt of Earth's axis of rotation with respect to the plane of its orbit and oscillates with a period of some 41 000 years. Precession **(c)** consists of the spin of Earth's rotational axis and its orbital path over time; the combined effects of those two components produce an approximately 21 000-year cycle. (Adapted from ref. 3.)

Three scientists joined forces 30 years later to verify Milanković's theory using deep-sea sediment cores collected by the international Ocean Drilling Program. James Hays examined marine microfossils in the cores to estimate past sea-surface temperatures. Nicholas Shackleton measured the oxygen isotope composition in the sediment's layers, which showed changes in past global ice volume. And the last member of the team, John Imbrie, brought an expertise in time-series analysis to the project. In 1976 they published a seminal paper showing that their climate record contained the same temporal cycles as three parameters, summarized in figure 1, that describe Earth's orbit: eccentricity, obliquity, and precession.[2]

Eccentricity describes the shape of Earth's orbit around the Sun. As Earth experiences a gravitational force from Jupiter, its orbit adjusts during a 96 000-year period from nearly a perfect circle to an ellipse, which causes minor variations in total insolation. Obliquity—the tilt of Earth's axis of rotation with respect to the plane of its orbit—fluctuates during a period of 41 000 years between 21.8° and 24.4° and is currently at 23.4°. A larger obliquity generates a greater difference in the insolation Earth receives during summer and winter.

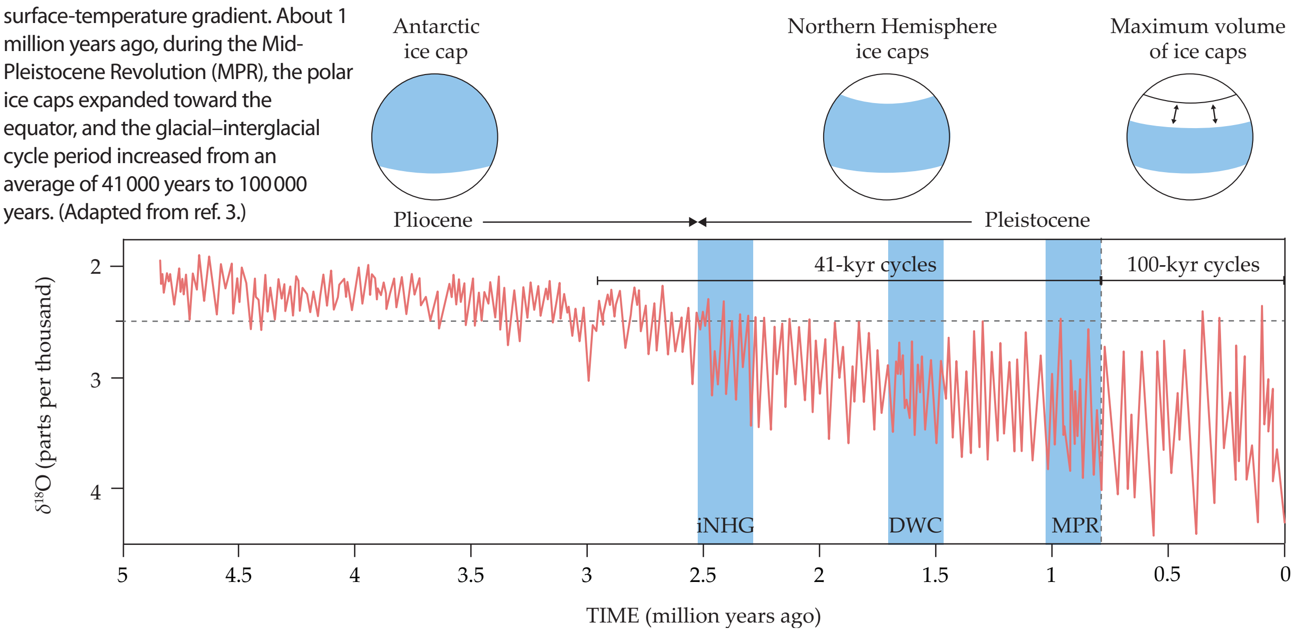
The third orbital parameter, precession, occurs every 21 700 years and influences Earth's closest approach to the Sun. During each hemisphere's summer, precession has the greatest effect in the tropics. Tidal forces of the Sun and Moon, amplified by Earth's oblate spheroid shape, cause one component of precession. Those forces exert gyroscopic motion on the planet that changes the orientation of its rotational axis. The second component of precession moves Earth's entire orbit around the Sun in space and resembles the petals of a flower, as shown in figure 1c.

The great ice ages

Over the past 2.5 million years, Earth has undergone some 50 major ice ages and each has substantially changed the planet's climate.[3] During the last one 21 000 years ago, a nearly continuous ice sheet spanned North America. At its thickest, across what is now Hudson Bay, it was more than two miles deep and reached as far south as New York City and Cincinnati, Ohio. The British–Irish ice sheet spread as far south as Norfolk, and the Scandinavian ice sheet extended from Norway to the Ural Mountains in Russia. In the Southern Hemisphere, large ice sheets covered Patagonia, South Africa, southern Australia, and New Zealand. So much water was locked in all those ice sheets that global sea level dropped 120 m, yet if all the Antarctic and Greenland ice melted today, sea level would rise only by 70 m.

How did small wobbles in Earth's orbit cause those ice ages? Summer temperatures must first decrease a little bit. The con-

FIGURE 2. MANY GLACIAL–INTERGLACIAL CYCLES (red solid line) during the last 5 million years can be seen from measurements of the oxygen isotope composition of lake records. Large ice sheets started to grow in North America 2.5 million years ago during the intensification of Northern Hemisphere glaciation (iNHG). The development of the atmospheric Walker Circulation (DWC) started 1.7 million years ago in the Pacific Ocean and is sustained by a large east-to-west sea-surface-temperature gradient. About 1 million years ago, during the Mid-Pleistocene Revolution (MPR), the polar ice caps expanded toward the equator, and the glacial–interglacial cycle period increased from an average of 41 000 years to 100 000 years. (Adapted from ref. 3.)



sequent accumulation of snow and ice increases Earth's albedo—the reflection of sunlight to space. Reflecting more sunlight suppresses local temperatures and promotes more snow and ice accumulation, which increases the albedo further. The process, called an ice–albedo feedback, is responsible for building increasingly bigger ice sheets.

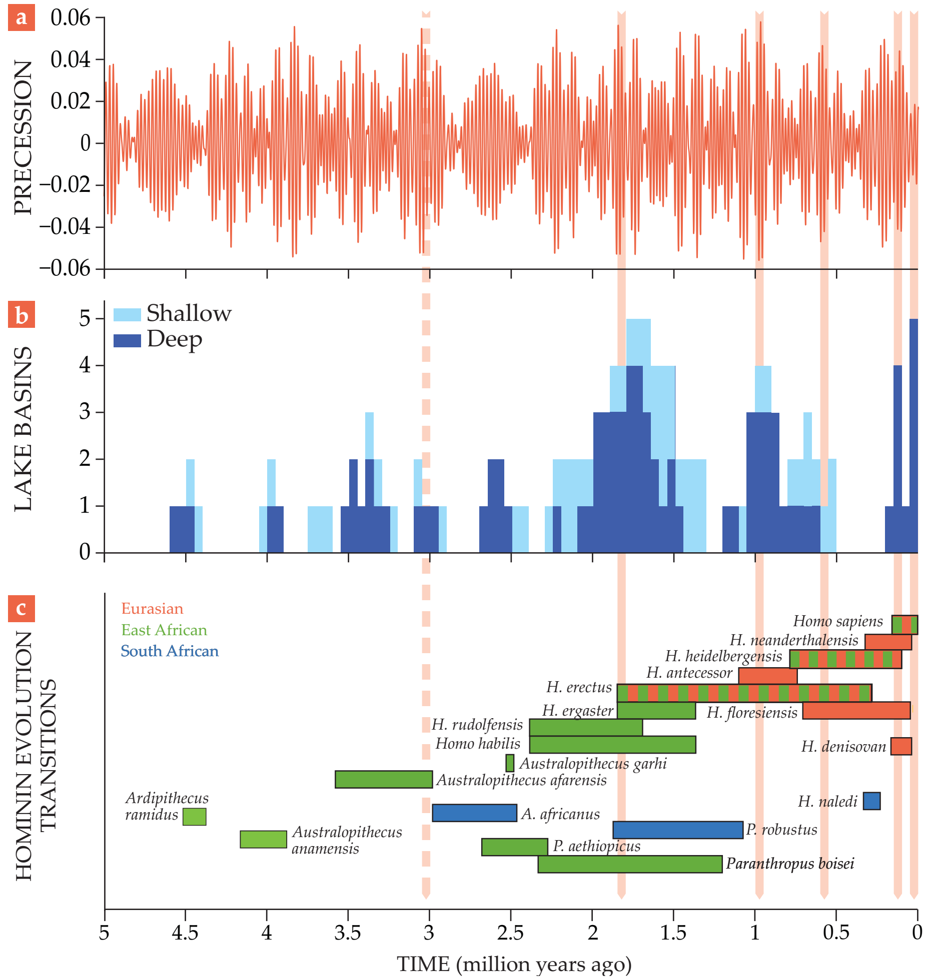


FIGURE 3. HUMAN EVOLUTION is connected to African climate change. Large variations in the precession of Earth's orbit **(a)** help determine the size and number of deep freshwater lakes in the East African Rift Valley **(b)**. Those lakes, in turn, can be linked to major evolutionary changes in early humans **(c)**. The red dotted line marks the first dispersal of hominins throughout Africa; solid red lines identify the times when hominins dispersed from Africa to Europe and Asia. (Adapted from ref. 8.)

Another positive feedback cycle triggers when ice sheets, such as the Laurentide sheet that once covered much of North America, become big enough to deflect atmospheric planetary waves. The change redirects storm paths across the North Atlantic Ocean and prevents the Gulf Stream and its northeastward arm, the North Atlantic Drift, from penetrating as far north as they do today. The surface ocean effects, combined with melt-water increase in the Nordic Seas and the Atlantic, cause a decrease in the sinking of cold, salty water (see PHYSICS TODAY, April 2019, page 19). As less water in the North Atlantic is driven to the deep ocean, the Gulf Stream pulls less warm water northward, and increased cooling in the Northern Hemisphere expands the ice sheets.

Greenhouse gases (GHGs) in the atmosphere reinforce ice-sheet feedbacks. Analyses of air bubbles trapped in polar ice indicate that during glacial periods carbon dioxide concentrations dropped by a third and methane by half. Changes in GHGs always precede variations in global temperatures and are therefore a clear driving force of climate change, not a response to it.[4]

Runaway positive feedbacks froze most of Earth's water billions of years ago during snowball Earth events, but moisture limitation has prevented a more recent episode. Forming an ice sheet requires a cold, wet climate. But as an ice sheet forces warm surface water farther south, the supply of moisture decreases. By changing the atmosphere and ocean circulation, ice sheets starve themselves of moisture, and that negative feedback loop limits the effects of positive ones.

For the past million years, ice sheets have taken at least 80 000 years to reach their maximum extent, which occurred most recently about 21 000 years ago. However, ice melts much quicker than that: 80% of expanded ice sheets can be lost in 4000 years. Summer sunshine at 65° N triggers deglaciation and starts the melting of Northern Hemisphere ice sheets. Rising concentrations of carbon dioxide and methane in the atmosphere promote climate change and further melt large continental ice sheets. Such processes work against the ice–albedo effect, which acts to keep the ice sheets intact by producing a cooler microclimate.

Ultimately, rising sea levels diminish large ice sheets because the coldest that seawater can be is −1.8 °C, whereas the temperature of the ice sheet's base is −30 °C. As seawater melts the ice sheets by undercutting them, ice calves into the ocean. The calving raises sea level further and causes more undercutting (see PHYSICS TODAY, October 2019, page 14). The sea-level feedback mechanism can be extremely rapid. Once the ice sheets are retreating, the other feedback mechanisms—albedo, atmospheric and ocean circulation, and GHGs—are reversed. That's why glaciologists and climatologists worry about future climate change: It will activate those feedbacks and cause irreversible instability to the Greenland and West Antarctic ice sheets (see PHYSICS TODAY, July 2014, page 10).

The eccentricity myth

The last million years of glacial–interglacial cycles, each lasting about 100 000 years, have a saw-toothed pattern with a long period of cooling followed by a short, warm one of rapid melting. More than a million years ago, the cycles were smoother, and each lasted only 41 000 years, as shown in figure 2. That period corresponds to the length of the orbital change associated with obliquity, which controls the heat transfer between low and high latitudes and thus regulates ice growth.

For many years, scientists struggled to explain the 100 000-

year glacial–interglacial cycles because the 96 000-year eccentricity mechanism has a similar length. But eccentricity is by far the weakest of the orbital variations, and many thought it predominantly modulated precession, so scientists suggested several nonlinear feedbacks to explain the discrepancy. But they found an answer when they realized that the 100 000-year cycle is a statistical artifact.

The average length of the last eight cycles is indeed 100 000 years, but each one varies from 80 000 to 120 000 years. Every fourth or fifth precessional cycle is weak enough that ice sheets can grow bigger and thus more vulnerable to sea-level rise during deglaciation. The next precessional cycle is always much stronger than the previous one and initiates rapid, extreme deglaciation through the sea-level feedback.[5] Although the timing of deglaciation seems to better match precession, some researchers have argued that the long glacial–interglacial cycles may correspond to every second or third obliquity cycle.[6]

Celestial mechanics and human evolution

In addition to high-latitude climate, orbital forcing also greatly influences the climates of tropical Africa, Amazonia, and Asia, particularly through precession. Climate models show that precession forcing increases annual precipitation in the tropics by at least 200 mm per year and significantly shifts the timing of seasons.[7] Such a change in moisture availability is equivalent to switching from a glacial period to an interglacial one. The influence of precession further increases every 96 000 years when eccentricity peaks, and it is greatest once every 413 000 years when Earth's orbit reaches its most elliptical.

Precession affects tropical climate by changing what time of year coincides with the closest Sun–Earth distance and thus the amount of insolation received during each season. (Eccentricity controls what that Sun–Earth distance is.) For example, during Northern Hemisphere summer, the tropics and subtropics heat up as the Sun steadily moves from directly overhead at the equator to the Tropic of Cancer at 23° N. At the maximum positive precession, the Sun–Earth distance will be shortest when the Sun is overhead at the Tropic of Cancer, and so the amount of solar energy and convection reaching the subtropics significantly increases.

The strengthened trade winds empower the Intertropical Convergence Zone and greatly increase the amount of rainfall in the Northern Hemisphere tropics (see the article by Thomas Birner, Sean Davis, and Dian Seidel, PHYSICS TODAY, December 2014, page 38). Meanwhile, Southern Hemisphere summer will coincide with the longest Sun–Earth distance, and rainfall will be greatly reduced in the tropics south of the equator. The situation reverses 21 000 years later, and the Southern Hemisphere tropics then become the place with the most intense insolation and rainfall.

Many paleorecords show the inverse relationship of each hemisphere's hydrological cycle. During the past 10 000 years, North African lakes have steadily been drying, while Amazon River discharge has increased.[8] Starting 5 million years ago, marine-dust evidence from the eastern Mediterranean Sea shows periodic increases in aridity in the eastern Algerian, Libyan, and western Egyptian lowlands.[8] Corroborating those records are sediment observations from the Arabian Sea, the North Atlantic Ocean, and the ocean adjacent to the West Africa coast. Records from sapropel formations—the dark organic-

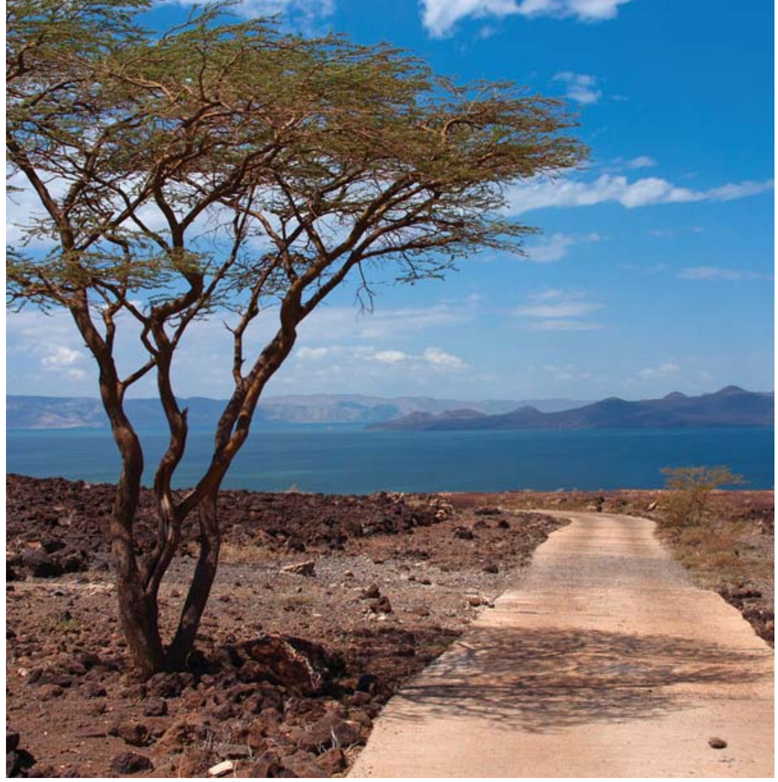


FIGURE 4. THE DEEP, EAST AFRICAN LAKE TURKANA experienced extreme wet and dry episodes during periods of high orbital forcing. Big swings in the precession of Earth's orbit create significant variations of the area's local insolation and rainfall intensity. Those variations lead to ephemeral deep freshwater lakes, like the one pictured here, in the East African Rift Valley. Scientists think that major developments in human evolution are linked to the short periods of highly variable environmental conditions. As the lakes dried out at the end of a precessional cycle, humans' brain size may have increased in response to the environmental pressure. (Belikova Oksana/Shutterstock.com.)

rich layer found in Mediterranean marine sediments that are made by a reduction in the oxygen content of the water—show increased rainfall and higher river discharge to the sea, and the variation in those records has a dominant periodicity of 21 000 years, which indicates precessional orbital forcing.

Climate reconstructions of the times when prehistoric hominin populations were evolving show a strong link between orbital forcing and the African environment. Eccentricity maxima generated periods of extreme climate variability every 400 000 years, which caused lakes to repeatedly grow and fill much of the African Rift Valley and then disappear on approximately a 20 000-year precessional time scale.[9] Shown in figure 3, those periods indicate statistically significant correlations with the majority of the first and final appearances of hominin species during the last 5 million years.[10,11]

The speed at which deep freshwater lakes, such as Lake Turkana in northern Kenya (shown in figure 4), appeared and disappeared from the landscape may have stressed the hominin species living in the region. Although orbitally forced climate oscillations operate on time scales longer than the rapid changes observed in lakes, all orbital parameters are sinusoidal, which means that periods of little or no variation are followed by ones with large changes. For example, the sinusoidal precessional forcing at the equator consists of periods of less than 2500 years during which 60% of the total variation in daily insolation and seasonality occurs. Those stretches of time are followed by ones that last 8000 years with relatively little change in daily insolation. The mismatched time scales produce brief stretches of strong forcing and long ones of relatively weak forcing. Combined with the idea that many East African lakes are amplifier lakes that respond quickly to small changes in the precipitation–evaporation balance, the landscape and climate may have responded swiftly to precessional forcing.

Anthropologists and climatologists have suggested that the presence or absence of lakes is associated with hominin dispersal events, which took place 3 million years ago in Africa and in other areas 1.8, 0.9, 0.6, and less than 0.1 million years ago.[8] Hominin migration would have most likely occurred when the basins were completely filled with water and both food and water were abundant. Hominins could have followed the Nile River's tributaries northward through a green Levant region, the area due east of the Mediterranean.[10]

Some evidence shows that early humans took multiple routes from Africa to the Middle East.[11] Wet conditions in East Africa correlate with a similar climate in the Levant and the Middle East. With each successive precessional cycle, deep freshwater lakes would have enabled hominin populations to migrate northward to the Ethiopian highlands, the Sinai peninsula, and, for a smaller population, southern Africa.

Creating a super-interglacial

To predict the next ice age, scientists are studying not only orbital forcing but also GHG emissions. Air bubbles trapped in the Greenland and Antarctic ice sheets show low GHG concentrations during cold glacial periods and high concentrations during warm interglacial times. Carbon dioxide usually varies between 180 ppm and 280 ppm and methane from 350 ppb to 700 ppb. Atmospheric carbon dioxide peaks as the Earth system rebounds from an ice age, and then it steadily declines until reaching a critical value of 240 ppm. (That level is 40 ppm lower than preindustrial times and more than 170 ppm lower than today.) At the critical value, orbital forcing pushes Earth's climate to another ice age, and glaciers grow slowly until eventually full glaciation is reached. Without human interference, ice sheets should have been growing now, and the next glaciation would have happened sometime during the next 1000 years.[12]

Paleoclimatologist William Ruddiman recognized odd GHG trends during the current interglacial period, the Holocene.[13] Ice-core records for each of the last eight warm interglacial periods show that GHGs begin at high levels and then slowly decline. But carbon dioxide started to rise some 7000 years ago and methane, about 5000 years ago, and those gases haven't declined as expected. Ruddiman suggested that human deforestation of land for agriculture, including the massive expansion of wet rice farming and domestication of cattle, caused the rise in atmospheric carbon dioxide and methane.

The extended interglacial period caused by persistently high GHG emissions produced an unusually stable climate and may have helped human empires emerge. Those emissions, however, are small compared to what humans have emitted since the start of the industrial revolution. Atmospheric carbon dioxide has increased by 47% to more than 410 ppm and methane by some 250% to more than 1860 ppb. Depending on future carbon emissions, global temperatures could rise 1.5–5.6 °C during the next century.[14] The GHGs already emitted have delayed the

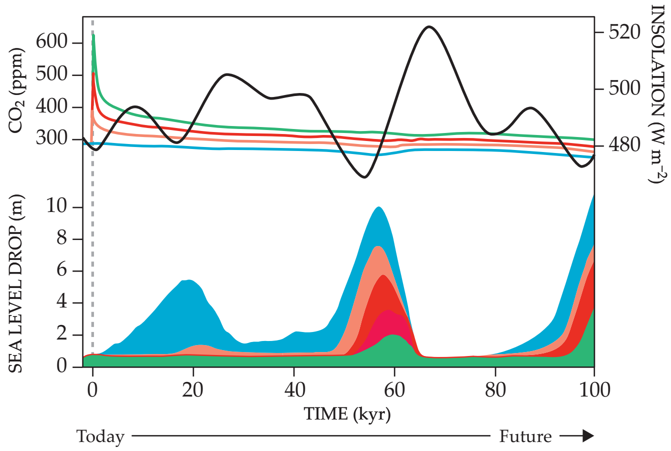


FIGURE 5. FUTURE ICE AGES depend on orbital forcing and on the quantity of greenhouse gases humans will emit (colored lines) during the next 100 years. The four corresponding emission scenarios graphed here from climate model simulations—green illustrates the highest emissions, followed by red, orange, and blue—show that anthropogenic climate change dwarfs the effect of orbital forcing and could delay the next ice age for 60 000 years. (Adapted from ref. 15.)

next ice age for 60 000 years, as shown in figure 5, according to climate models.[15] If the emissions reach the highest predicted level, glaciation would be delayed for 0.5 million years. Human fossil-fuel use has created a super-interglacial period that has overridden the effect of orbital forcing on Earth's climate.

The Quaternary may still be an appropriate term for the current geologic epoch if humans have delayed the next ice age. But if humans have permanently altered glaciation processes in the Earth system, some scientists propose naming the current period the Anthropocene.[16] The knowledge of orbital forcing has provided scientists with a framework to understand past environmental changes, and the knowledge gained may improve researchers' ability to predict the future environment.

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