SECOND CASE STUDY

The Orbit of Earth and Pleistocene Glacial Rhythms

The first unequivocal evidence of a large Antarctic ice cap is the occurrence of ice-rafted detritus in deep-sea cores dated at 28 million years of age. (Ice-rafted detritus is an indicator that continental ice carrying material eroded from the continents was transported out to sea by icebergs.) Greenland was clearly glaciated 3 million years ago. A closer examination of the record of glaciation during the last 1.9 million years (the Pleistocene) reveals considerable climatic variability in the form of repeated advances and retreats of the polar ice caps.

The movement of ice over the land surface is an extremely destructive process, mechanically grinding the rock surface and carrying the glacial debris downstream. On land the history of glaciation is recorded by glacial tracks and scours and by the deposition of glacial debris at the front (terminal moraines) and sides of glaciers and ice caps. In North America and Europe four major groups of terminal or end moraines are preserved from the Pleistocene. Does this record suggest four major glacial advances of the modern ice cap? Moraines give scientists only the evidence of the farthest extent of glaciation. A more recent glaciation would destroy the record of any previous ice age where the maximum extent of the ice was less than that of the most recent advance. Until 1950, the end moraines were the only record of the ice age, and only four major glaciations were identified.

A much better record was derived from the deep sea with the invention of coring devices in 1950. The coring of oceanic sediments retrieved a continuous record of microscopic fossil shells composed of calcium carbonate ($CaCO_3$). This new-found record was examined in detail with an innovative chemical methodology based on isotopes.

A chemical element is defined by the number of protons in its nucleus. The number of neutrons in the nucleus can vary. Isotopes are elements with different mass numbers defined by the total number of neutrons and protons. Because isotopes have different masses, different physical and chemical processes may separate, or fractionate, them. For example, oxygen has three isotopes: oxygen-16, -17, and -18. In the process of evaporation from the surface of the ocean, water containing oxygen with the lightest isotope value is preferentially evaporated. Likewise, in precipitation there is a preference to rain out water with the heaviest isotope, oxygen-18, first. The atmosphere is, in a sense, distilling the oxygen isotopic composition of the moisture it transports through the processes of evaporation and precipitation. The moisture that is finally deposited on the ice caps is extremely enriched in the light isotope, and therefore, during times of extensive glaciation, the ocean becomes depleted in oxygen-16. The microscopic organisms in the ocean that grow $CaCO_3$ shells preserve the oxygen isotopic composition of the oceanic water in which they live and build their shells.

The record of oxygen isotopes for the last 700,000 years (Figure 10) reveals a remarkably rhythmic record of repeated glaciation. More oxygen-18 recorded by shells indicates more of the lighter oxygen-16 stored as ice on land. Note that the oxygen-18 record for each ice age has a similar amplitude and that the record for each ice age has a ramp-like structure suggesting slow buildup to full glaciation and then rapid retreat. The current climate is best described as "interglacial" and the last major ice advance ("glacial") was approximately 18,000 years ago.

A wide variety of theories has been presented to explain these glacial cycles, involving Earth orbital variability, volcanism, variations in the magnetic field of Earth, solar variability, interstellar dust, internal oscillations, Antarctic ice surges, atmospheric carbon dioxide concentration, and deep ocean circulation changes. The remarkably rhythmic nature of the glacial cycles, undiscovered until more complete records from the deep sea were collected, has proven to be a major test for the theories of glaciation. A deterministic view of the climatic system would suggest that the glacial-interglacial rhythms were the product of some periodic climatic forcing factor.

In the first half of the twentieth century, Milutin Milankovitch, a Yugoslavian astronomer, proposed that periodic changes in Earth's orbital characteristics were the major control over glaciation. Milankovitch computed periods for the variation in the time of year during which Earth is closest to the Sun, governed by the orbital precession of the equinoxes (approximately 19,000 to 23,000 years—see discussion below); the axial tilt of Earth approximately 41,000 years); and the eccentricity of Earth's orbit around the Sun (approximately 100,000 years). Milankovitch's hypothesis was rejected at the time due to the weight of evidence from continental regions suggesting that there were only four major glaciations.

James Hays, John Imbrie, and Nick Shackleton revitalized the Milankovitch hypothesis when they calculated the timing of variations for three geologic factors—surface temperature, oxygen isotopes, and the abundance of a particular plankton species—from high-resolution, continuous deep-sea cores representing the last 700,000 years (see their paper in the Recommended Additional Reading). They found that these variables illustrated a rhythm with intervals of 19,000, 24,000, 43,000, and 100,000 years (Figure 11). The dominant climatic periodicity is 100,000 years. The correspondence of the periods from the geologic data with the periods of the Earth's orbital characteristics is unmistakable.

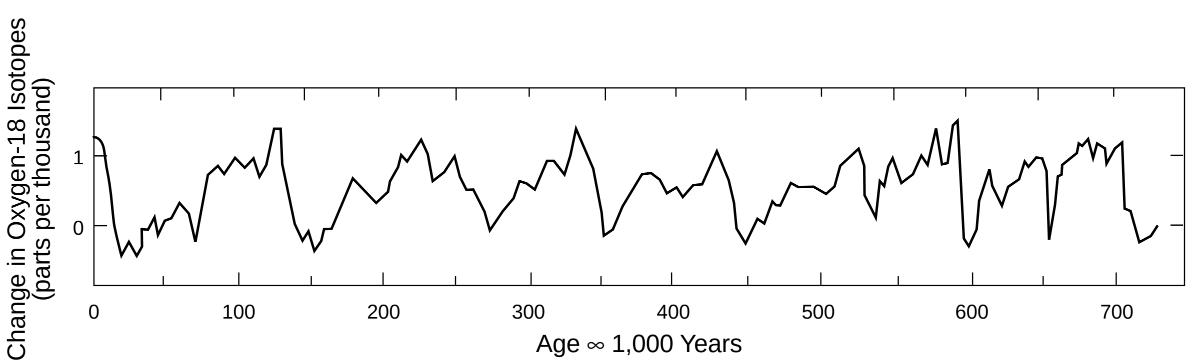

Figure 10. Oxygen isotopic record for the last 700,000 years, illustrating glacial/interglacial cycles (after Emiliani, 1978). Higher oxygen-18 levels show interglacial periods.

The Orbital Elements and the Insolation of Earth

The gravitational effects of the planets within our solar system perturb the orbit of Earth. Since the input of solar energy is dependent on the distance between Earth and Sun and on the solar angle, these orbital changes alter the seasonal and latitudinal distribution of incoming solar energy (called insolation).

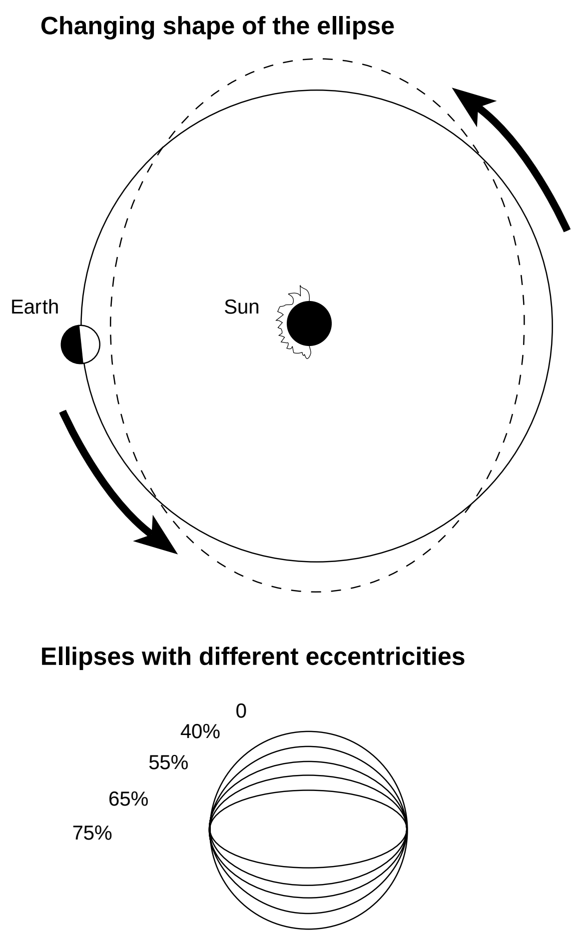

Figure 11a. The orbit of Earth changes shape from nearly circular to more elliptical. This is termed eccentricity and is expressed as a percentage (after Imbrie and Imbrie, 1979).

Eccentricity

Due largely to interactions with Jupiter and Saturn, the orbit of Earth about the Sun varies from a circle (an eccentricity of 0) to an ellipse (a maximum eccentricity of .07), with a period of 96,600 years (Figure 11a). The Sun is currently nearest Earth in January and farthest away in July. During periods of maximum eccentricity, the differences in Earth-Sun distance from summer to winter can greatly accentuate the contrast between the seasons. However, on an annual average, variations in the eccentricity result in less than a 1% range in the total insolation.

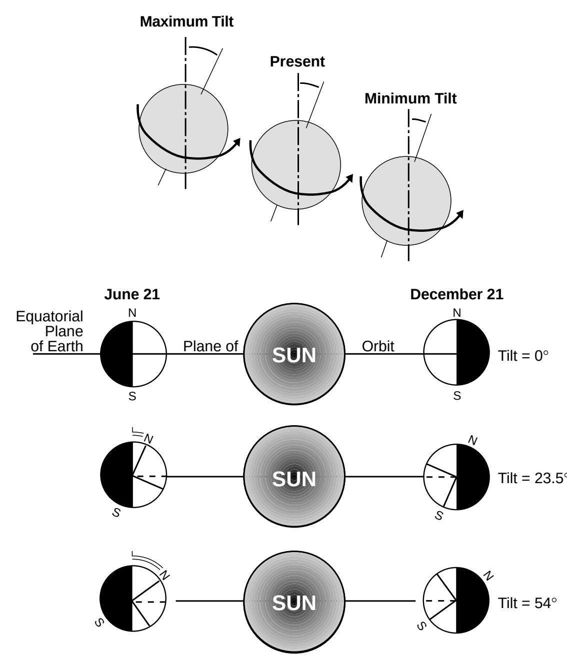

Figure 11b. Variation in the tilt of Earth's axis from maximum to minimum, and the effect of axial tilt on the distribution of sunlight. When the tilt is decreased from its present value of 23.5°, the polar regions, in summer, receive less sunlight; when the tilt is increased, polar regions receive more sunlight (after Imbrie and Imbrie, 1979).

Obliquity

The obliquity of Earth is measured as the tilt of Earth's axis from the normal to the plane of its orbit (Figure 11b). Today the obliquity is 23.4 degrees (the latitude of the tropics of Cancer and Capricorn). With a period of 41,000 years the obliquity varies from 22 degrees to 24.5 degrees. The condition of higher obliquity (greater tilt toward and away from the Sun) produces more pronounced differences between winter and summer seasons and greater total solar energy at the polar region. The condition of low obliquity (less tilt) reduces the seasonal cycle, but a smaller amount of insolation is received in polar regions during the year. The variation in obliquity produces a difference of approximately 10% in polar insolation.

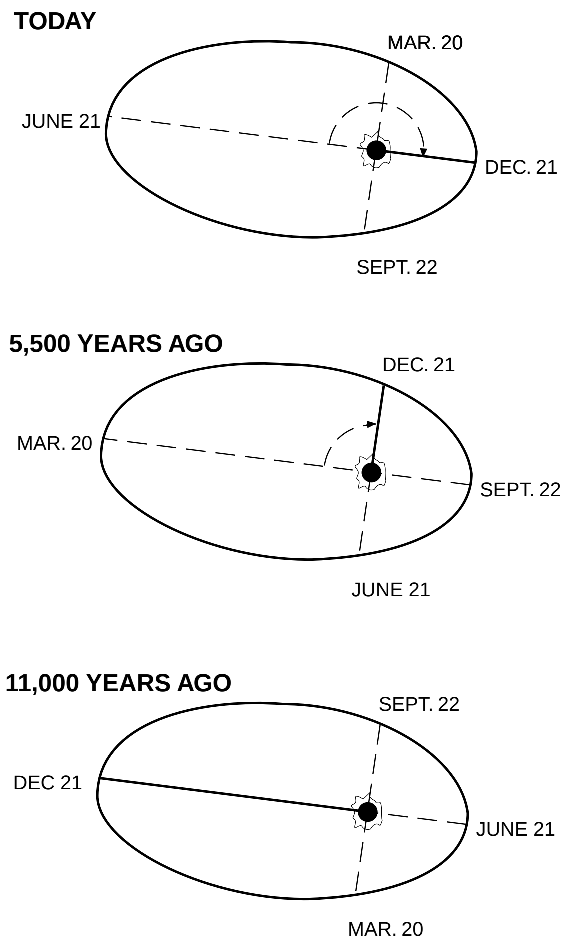

Figure 11c: Precession of the equinoxes. Owing to axial precession and to other astronomical movements, the positions of equinox (March 20 and September 22) and solstice (June 21 and December 21) shift slowly around Earth's elliptical orbit, and complete one full cycle about every 22,000 years. Eleven thousand years ago, the winter solstice occurred near one end of the orbit. Today, the winter solstice occurs near the opposite end of the orbit.

Precession of the Equinoxes

Solar and lunar torques on the equatorial bulge of Earth cause the time of perihelion (the time at which Earth is closest to the Sun) to vary

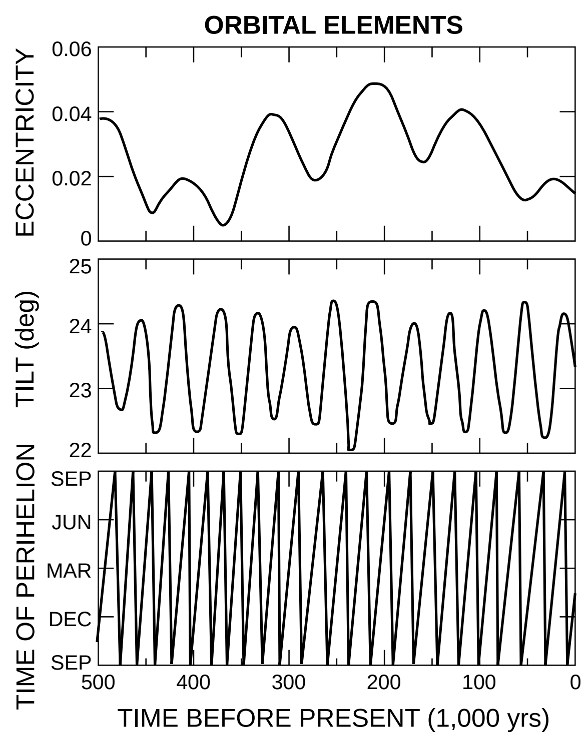

Figure 12. Variations in Earth's orbital elements, eccentricity, tilt (obliquity), and time of perihelion (precession of the equinoxes) computed for the last 500,000 years with a computer program written by Tamara Ledley and Starley Thompson following Berger (1988).

(Figure 11c). Currently, perihelion is in January, tending to moderate Northern Hemisphere winters. Ten thousand years ago, the time of perihelion was in Northern Hemisphere summer, resulting in a much more pronounced seasonal cycle. The precession of the equinoxes has a period of approximately 21,000 years. Combined with eccentricity, differences in the time of perihelion can result in differences of as much as 33 days in the length of astronomical summer and winter.

Figure 12 illustrates the variations in Earth's orbital elements—eccentricity, tilt (obliquity), and time of perihelion (precession of the equinoxes)—as computed for the last 500,000 years by Andre Berger. From the orbital variation (knowledge of the distance between Earth and Sun and the solar angle) the variations in insolation (Figure 13) can be determined. There is little change in the global, annual-average insolation; however, there are relatively large changes in the amplitude of the seasonal cycle and in the receipt of solar energy at high latitudes. In Figure 13 the Northern Hemisphere insolation varies by as much as 9% on either side of the mean insolation value.

These calculations can be extended back in time for approximately 5 million years, at which point phase relationships and the amplitude of the variations cannot be accurately reconstructed.

Explanations of Glacial Rhythms

The acceptance of Milankovitch's hypothesis, that orbital cycles provided the pacemaker for the ice ages, provides the basis for a unique case study of global climatic change. The mechanism is apparently known and the geologic record illustrates a well-defined "response," which can be the basis for examining climatic sensitivity to an external forcing factor. Much of the research has focused on developing the physical explanations required to substantiate the statistical association demonstrated by Hays, Imbrie, and

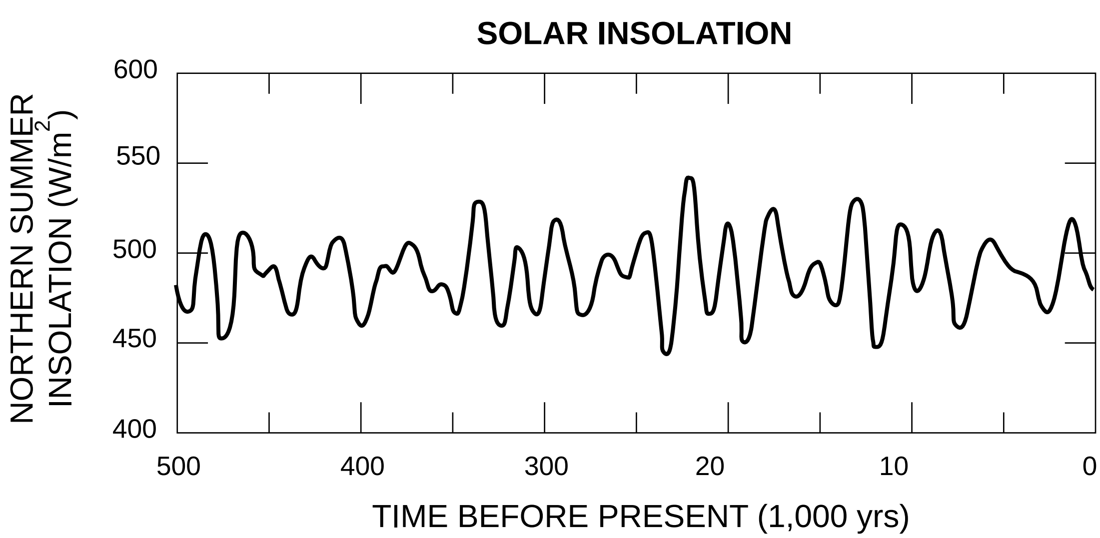

Figure 13. Variations in insolation (in watts per square meter) determined from the variations in Earth's orbital elements.

Shackleton in 1976 (see their paper in the Recommended Additional Reading).

The complex general circulation models (GCMs) utilized in the investigation of Cretaceous warmth require too much computer time to simulate the thousands of years of glacial climate. Climatologists instead have turned to simpler models governed by consideration of Earth's energy balance. Max Suarez (University of California, Los Angeles) and Isaac Held (NOAA Geophysical Fluid Dynamics Laboratory) made one of the early attempts to verify the Milankovitch theory with a climate model. Their energy balance climate model was zonally symmetric and included seasonal changes in the insolation.

In this model, changes in snow cover (simply based on predicted surface temperature) and associated changes in albedo play the dominant role in determining the sensitivity of the model to orbital changes. The model results showed substantial sensitivity to orbital variations (a 2.4°C difference in Northern Hemisphere temperature between different orbital conditions). The results indicated significant sensitivity to obliquity and precession.

However, two problems were evident: (1) the models failed to reproduce the dominant 100,000-year cycle of glaciation and the ramp-like nature of the glacial growth and decay, and (2) the models failed to reproduce a lag between insolation changes and the buildup and decay of glaciation. The results are not unexpected. Eccentricity alone does not have a major influence on insolation, and a 100,000-year rhythm is not evident in the insolation calculation illustrated in Figure 13. What could explain the discrepancies?

The discrepancies noted from the early attempts to simulate glacial rhythms are a road map to improvement of climate models. The simulation's lack of a lag between cause and effect suggests that some of the long time constants of the climate system must be considered, such as deep-ocean processes and ice-sheet dynamics. The inability to simulate the 100,000-year signal guides us to a consideration of other forcing factors and other amplifiers or modulators of the climatic response. In summary, the research on the ice ages began to focus our attention on some of the slower "physics" of the climatic system, most notably ice-sheet dynamics.

The first step was to add an ice sheet to the energy balance model in order to include climatic system inertia based on the volume of the ice sheets. When the model was run, the simulated changes in ice-sheet volume were 20 to 50% of the observations (Figure 14), and only the oscillations due to obliquity and precession were apparent. The second major step was to include the response of the lithosphere to ice-sheet buildup. Essentially, the weight of the ice sheet depresses the lithosphere.

Johannes Oerlemans of the University of Utrecht, Netherlands, suggested that after extensive growth of the ice sheet, the slow sinking of the bedrock might bring much of the ice sheet below the snowline, resulting in rapid deglaciation. When they set the bedrock response time to ice loading at 10,000 years, they were able to simulate the ramp-like nature of the 100,000-year glacial cycle.

Problems still remain, however. Although the simulations are now qualitatively in line with the observations, they do not achieve the necessary magnitude of response to orbital variations. The most logical explanation is that the models are far too simple. Perhaps such factors as carbon dioxide concentration, topography, snow accumulation, or seemingly minor effects such as how fast ice sheets "calve," or break apart, must be included before the simulations provide a full explanation.

The association of glacial rhythms with variations in atmospheric carbon dioxide concentrations is particularly fascinating. The ice sheets consist of layers representing thousands of years of annual accumulation. Air bubbles trapped within the ice record the composition of the ancient air. The composition of the air throughout glacial cycles has been measured from ice cores, revealing a 200- to 280-ppm variation in carbon dioxide from glacial to interglacial conditions (Figure 15). Lower atmospheric carbon dioxide concentration during glacial episodes should intensify the response to orbital variations. Many hypotheses have been offered to explain these variations, including changes in plant productivity, changes in the deep-ocean circulation, and variations in nutrient availability.

Ice cap–bedrock feedbacks and the effect of atmospheric carbon dioxide concentration are not the only mechanisms under investigation to explain glacial cycles, nor is the scientific community in full agreement on the role of Milankovitch orbital variations. For example, several researchers have shown that different feedbacks, if sufficiently out of phase, can yield a limited cyclic behavior. In short, the complex interactions of the climatic system may produce rhythms even though the causative factors were not periodic.

Importantly, the glacial rhythm "case study" of climatic change suggests the interrelationships in the climatic system. Knowledge of several factors, in addition to the direct effect of orbital variations, is required to understand the rhythm of the ice ages, including ice-sheet dynamics, bedrock feedbacks, and the effect of atmospheric carbon dioxide concentration.

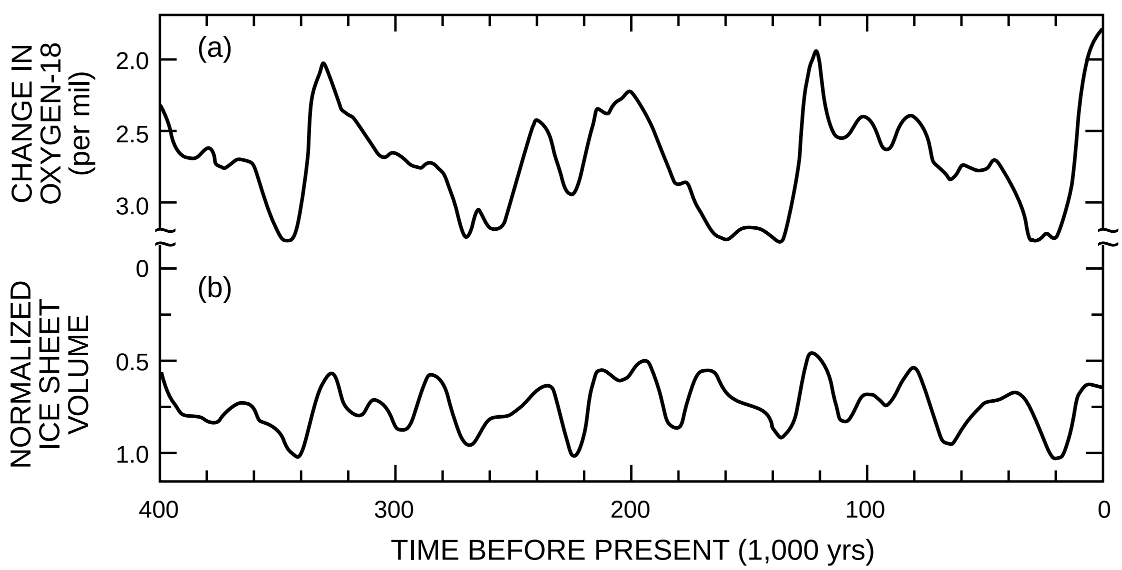

Figure 14. A comparison of (a) oxygen-18 record from Hays et al. (1976) with (b) an ice age simulation of Northern Hemisphere ice volume from the energy balance climate model with an explicit ice sheet formulation from Pollard et al. (1980). Note the correspondence of secondary cycles but the absence of the dominant ramp-like glacial-interglacial signal in the model simulation.

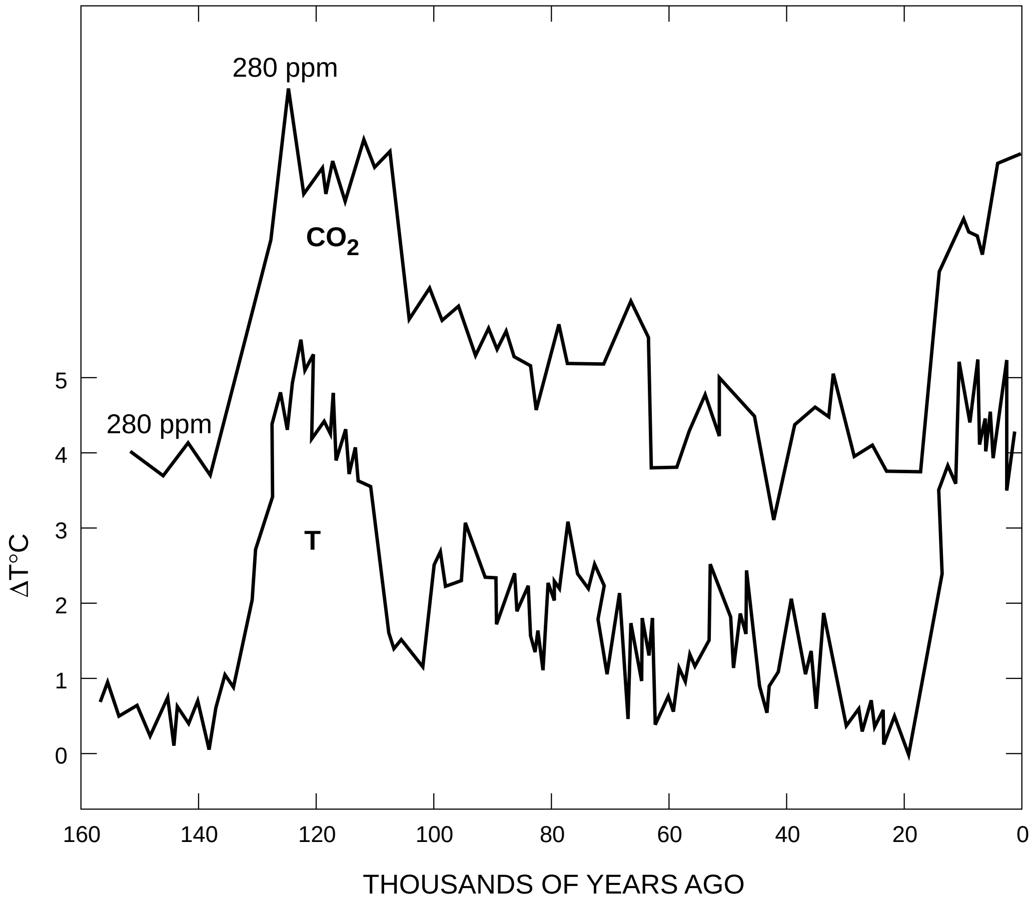

Figure 15. A comparison of the temperature history of Earth over the last 160,000 years with the carbon dioxide history recorded in bubbles trapped in glacial ice.