

ICE AGES (MILANKOVITCH THEORY)

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Introduction

An astronomical theory of paleoclimate aims to provide an understanding of the relationship between insolation and climate on the global scale. One such theory was developed by Milankovitch who first computed the radiation received by the Earth from the Sun (insolation). This quantity undergoes diurnal, seasonal, as well as millennial scale (long-term) variations. Milankovitch argued that insolation changes induce surface temperature changes and that long-term insolation changes are sufficient to produce ice ages by changing the geographic and seasonal distribution of sunlight received by the Earth. He estimated the relationship between summer radiation and the altitude of the snowline, which allowed him to compute the latitude of the ice sheet margin for the last 650 000 years. Milankovitch's curves were found to be remarkably consistent with the reconstruction of the glacial period made by Penck and Brückner. However, Milankovitch theory is not the only astronomical theory of paleoclimate. For example, in the nineteenth century, Croll developed an astronomical theory of paleoclimate, which was later rejected because it did not fit with the evidence of that time. Today astronomical theories are still a focus of research. Sophisticated climate models are used to test how insolation, and in particular its distribution in

latitude through the year, is forcing climate. Four main steps can be identified in an astronomical theory (Figure 1):

- the theoretical computation of the long-term variations of the Earth's orbital parameters and related insolations;
- the design of climate models to study climate changes related to insolation changes;
- the collection of geological data and their interpretation in terms of climate; and
- the comparison of these proxy data to the simulated climatic variables.

Therefore astronomical theory is at a crossing point of geology, astronomy, physics, chemistry, biology, and geophysics. Moreover, it is related to processes of the solid Earth, the atmosphere, the hydrosphere, and the ocean.

The Ice Ages

Our planet Earth was born some 4.5 billion years ago. Many events have marked its evolution; in particular, some periods have experienced markedly colder climate than others. Up to 0.9 billion years ago the Earth was apparently mostly ice-free, despite low solar luminosity, although there is some evidence for a first glaciation approximately 2.5 billion years ago. At least three major phases of glaciation occurred between 900 and 600 million years ago. Glacial deposits from the late Proterozoic have been found at low

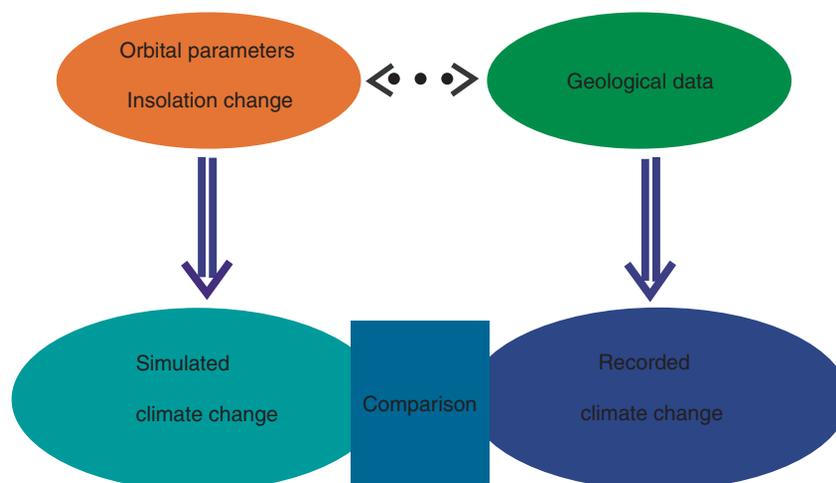


Figure 1 Schematic outline of an astronomical theory of paleoclimate.

latitudes, suggesting that at that time ice sheets covered the Earth from pole to pole. This is the so-called 'snowball Earth' hypothesis. The return to warmer conditions would then have resulted from the accumulation in the atmosphere of CO₂ from volcanic activity. The large cap carbonate found in Namibia, for example, could be the witness of this time. However, this hypothesis is still debated. From 600 to 100 million years ago mild climates prevailed, punctuated by several major phases of ice growth. These long geological cold periods, such as the late Precambrian Ice Age, the late Ordovician-Silurian Ice Age, and the Permo-Carboniferous Ice Age, are also called Ice Ages. A gradual cooling and drying of the globe started some 50 million years ago. The Antarctic ice sheet started to grow some 40 million years ago, whereas the Greenland and midlatitude ice sheets formed later (4–2.4 million years ago). The Quaternary Ice Age, the cold period in which we are living, is characterized by a succession of colder and warmer periods, the glacial–interglacial cycles. During colder phases (or ice ages) the ice sheets spread out in the high latitudes. The purpose of astronomical theory is to explain these broad climatic features, which characterize not only the Quaternary, but also older periods including the Early Mesozoic, more than 150 million years ago.

A Brief History of the Astronomical Theory of Paleoclimates

The inspiration for the pioneering work on the astronomical theory of paleoclimate was probably Louis Agassiz's lecture about his theory of a Great Ice Age at a meeting of the Swiss Society of Natural Sciences, held in Neuchâtel in 1837. Only a few years later, Joseph Adhémar proposed an explanation of the existence of ice ages based on the precession of the equinoxes. At the same time the French astronomer, Urbain Leverrier, calculated the changes in the Earth's orbit over the last 100 000 years. James Croll would eventually take Adhémar's idea and put it into an astronomical theory of climate. Croll's major hypothesis was that the critical season for producing an ice age is winter. He determined that the precession of the equinoxes must play a decisive role in the amount of sunlight received during winter. Indeed, winter would be warmer if it occurred when the Earth were closer to the Sun and it would be colder if the Earth were farther from the Sun. Moreover, the shape of the Earth's orbit could reinforce this effect. He concluded that periods of greater eccentricity could lead to exceptionally warm or cold winters. He argued that ice ages therefore occurred alternately in one hemisphere or

the other during Glacial Epochs, when eccentricity is large. According to Croll, the last Glacial Epoch began some 250 000 years ago and ended about 80 000 years ago. Later, he also took into account the role of the tilt of the Earth's axis of rotation. He hypothesized that an ice age would be more likely to occur when the tilt was small because the polar regions would then receive less heat. However, he acknowledged that orbital changes could only be a triggering mechanism. He identified the albedo–temperature feedback and the change in ocean currents as two mechanisms responsible for amplifying the direct climatic effect of the astronomical forcing. Meanwhile, geologists collected evidence around the world that several ice ages had occurred in the past, separated by nonglacial epochs, as predicted by Croll's theory. However, with time the majority of geologists in Europe and America became opposed to Croll's theory as more and more new evidence suggested that the last Glacial Period ended later than 15 000 years ago, instead of 80 000 years ago as required by Croll's astronomical theory. By the end of the nineteenth century, the theory fell into disfavor.

The attention of the scientific world was drawn back to the ice age problem with the publication in 1924 of Milankovitch's theory. This was the first full astronomical theory of the Pleistocene ice ages, including the computation of the orbitally induced changes in the insolation and climate. According to Milankovitch's theory, the summer in northern high latitudes had to be cold to prevent the winter snow from melting. In turn this would allow a positive value in the annual budget of ice, and a positive feedback cooling would be initiated over the Earth through a further extension of the snow cover and subsequent increase of surface albedo. This hypothesis requires that summer insolation is a minimum in the high latitude Northern Hemisphere. One of Milankovitch's first major contributions consisted of radiation curves showing past insolation changes at high northern latitudes (**Figure 2**). He claimed that each minimum of these curves should cause an ice age. Comparing Milankovitch's curves with the Penck and Brückner curve for the succession of European ice ages, Köppen and Wegener concluded that the theory matched the facts amazingly well. Although the timing of the ice ages and the radiation minima did not agree in detail, the general pattern of the two curves was quite similar. But by 1955, the astronomical theory was rejected by geologists. Indeed, using new techniques for dating Pleistocene fossils (radiocarbon dating) they showed that there were more glacial advances during the past 80 000 years (or at least the time interval believed to be 80 000 years) than could be explained by the Milankovitch theory.

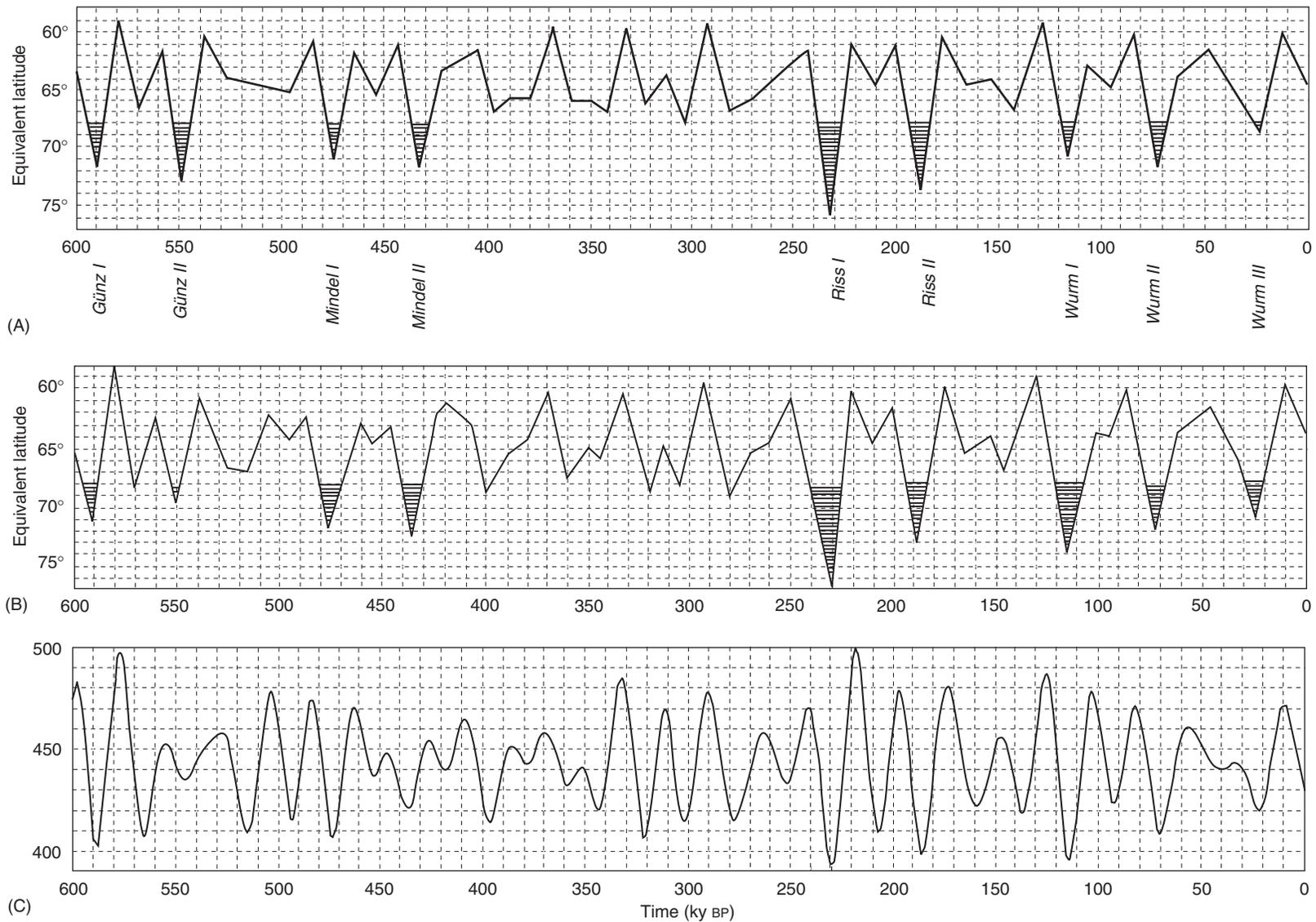


Figure 2 The Milankovitch amplitude of the secular variations of the summer radiation at 65° N, (A) after Stockwell and Pelgrim's, and (B) after Le Verrier and Miskovitch's astronomical solution. The ordinate axis in (A) and (B) gives the latitude that receives the same radiation as 65° N for the last 600 ky. Part (C) gives the mean irradiance (W m^{-2}) according to Berger's computation.

The theory was still largely disputed until the early 1970s. Nevertheless, progress was being made toward a better understanding of the ice ages, in particular the Pleistocene. New dating techniques were developed and accurate climatic interpretation was given to geological records, such as variation of the oxygen isotope records of forams in deep sea cores, or sequences of soils and loess. New evidence was put forward that major climate changes have accompanied variations in obliquity and precession over the last 500 000 years. This finding stimulated the revival of the astronomical theory. Vernekar, Bretagnon, Berger, and others refined the calculations of orbital history; geologists obtained new records of past climate; the improved dating techniques clarified the detail of the Quaternary time scale; global past climate changes were reconstructed with better accuracy; and finally, climate models were designed to test this theory. Within a few years it became increasingly clear that major changes in global climate were caused by changes in the astronomically driven insolation forcing. Moreover, the importance of mechanisms and processes such as the carbon cycle, vegetation change, ocean circulation, and dynamics of the cryosphere was also acknowledged.

Orbital Parameters

The German astronomer Johannes Kepler (1571–1630) formulated the three laws of planetary motion, which are satisfied with a high accuracy not only by the system of planets and Sun, but also by the system of each set of satellites moving about their primary planet. They are:

- The orbit of each planet is an ellipse with the Sun at one focus.
- The line (the radius vector) joining the Sun to each planet sweeps out equal areas of its ellipse in equal times.
- The cubes of the semimajor axis of the planetary orbits are proportional to the squares of the planets' periods of revolution.

While Kepler gave a description of the orbital motion, Sir Isaac Newton (1642–1727) defined the law of gravitation, which is the basis for explaining the planetary motion. In particular, during its travel counterclockwise on its orbit around the Sun (Figure 3), the Earth is sometimes nearer to and sometimes farther away from the Sun. The distance from the Earth to the Sun (r) can be computed through the equation of the ellipse, given here as eqn [1].

$$r = [a(1 - e^2)] \times (1 + e \cos v)^{-1} \quad [1]$$

In eqn [1], a , the semimajor axis of the orbit, gives its size. The value of a is constant through geological time to a very good accuracy. The eccentricity, e , is a measure of the departure of the ellipse from a circle, and the true anomaly, v , of the Earth is a measure of the position of the Earth in its orbit. The true anomaly is measured counterclockwise from perihelion (where the Earth is nearest to the Sun). Usually the angles that describe the position of the Earth in its orbit are not measured from the perihelion, but rather from the spring equinox (SE). Therefore, we have $v = \lambda - \omega$, where λ is the longitude of the Earth in its orbit measured from the spring equinox of the year, or moving spring equinox, and ω is the longitude of the perihelion relative to this same moving spring equinox. Alternatively, the position of the perihelion ($\bar{\omega}$) is often measured from the First Point of Aries (vernal point). This point on the Earth's orbit gives the direction of the Sun as seen from the Earth at the spring equinox. Consequently, we have $v = \lambda - \bar{\omega} - \pi$. In addition, the Earth's axis of rotation is tilted with respect to the orbital plane. The obliquity, ε , is the angle between the Earth's axis of rotation and the perpendicular to the orbital plane.

The astronomical parameters, e , ε , and ω , experience long-term variations. These variations can be obtained by solving two sets of equations, one set for the mutual gravitational forces in the planetary system and the other for the Sun–Earth–Moon system.

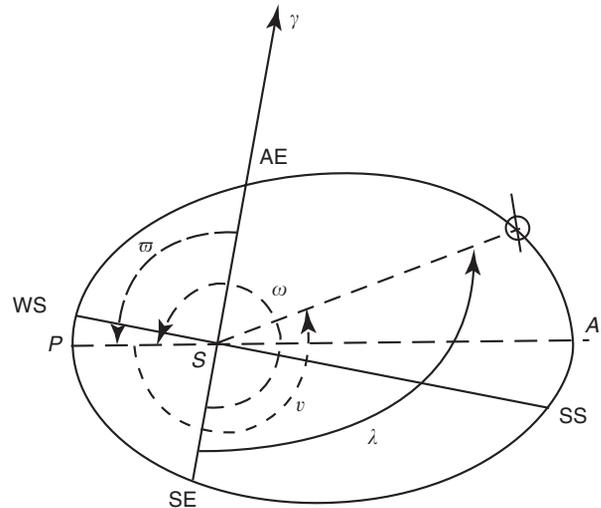


Figure 3 Elements of the Earth's orbit around the Sun (S). Some reference points are drawn on the orbit, i.e., the perihelion (P) and the aphelion (A), the spring equinox (SE), the summer solstice (SS), the autumn equinox (AE), and the winter solstice (WS). The vernal point is given by γ . λ is the longitude of the Earth in its orbit measured from the spring equinox of the year, or moving spring equinox; ω is the longitude of the perihelion relative to this same moving spring equinox; and v is the true anomaly measured counterclockwise from the perihelion.

Different methods, from fully analytical to fully numerical, were developed following the first calculations by Leverrier in the nineteenth century. Moreover, the accuracy of these solutions has been greatly improved. However, the orbital motion of the planets in the solar system is chaotic, i.e., the solution is strongly dependent on the initial conditions, which limits the possibility of obtaining an accurate solution for the astronomical parameters of the Earth over more than 35–50 million years.

Figure 4 shows the long-term variations of the three orbital parameters (e , ε , $e \sin \bar{\omega}$) from 400 000 years Before Present (400 ky BP) to 100 000 years After Present (100 ky AP), a time slice over which the solution is very accurate. The eccentricity of the orbit varies between near circularity ($e = 0$) and small ellipticity ($e = 0.07$). These variations are quasi-periodic with a mean period of about 100 ky. However, a longer period of about 400 ky can also be discerned. In practice, the analytical solution for the eccentricity, expressed in trigonometrical series, puts forwards many terms having different periods. The major periods in the development are 404, 95, 124, 99, and 131 ky (in order of decreasing amplitude). The obliquity (tilt of the Earth's axis) varies between 22° and 25° with a very clear quasi-period of 41 ky. The

largest amplitude terms correspond to periods of 41 (by far the largest term), 54, and 39 ky. The variations of the climatic precession ($e \sin \bar{\omega}$) reflect two opposing motions, i.e., the counterclockwise motion of the perihelion along the ecliptic with a period of ~ 100 ky and the clockwise motion of the vernal point along the ecliptic with a period of ~ 25 700 years. The two effects taken together result in the climatic precession, which corresponds to the slow shift of the seasons about the Earth's orbit relative to the perihelion. This motion has a mean quasi-period of 21 ky, which is derived from periods at 19 and 23 ky.

Insolation

The amount of solar radiation received at a mean Earth–Sun distance, r_m , by a surface perpendicular to the incident radiation, is about 1370 W m^{-2} (this is the so-called total solar irradiance, S_0). However, r_m varies over time according to the eccentricity. Therefore, instead of S_0 , it is often preferred to use the related quantity, S , defined at the constant distance a from Sun. As the solar energy decreases according to the square of the distance from the Sun, the amount of solar radiation received by the Earth on a unit surface perpendicular to the Sun's rays at a distance r from the

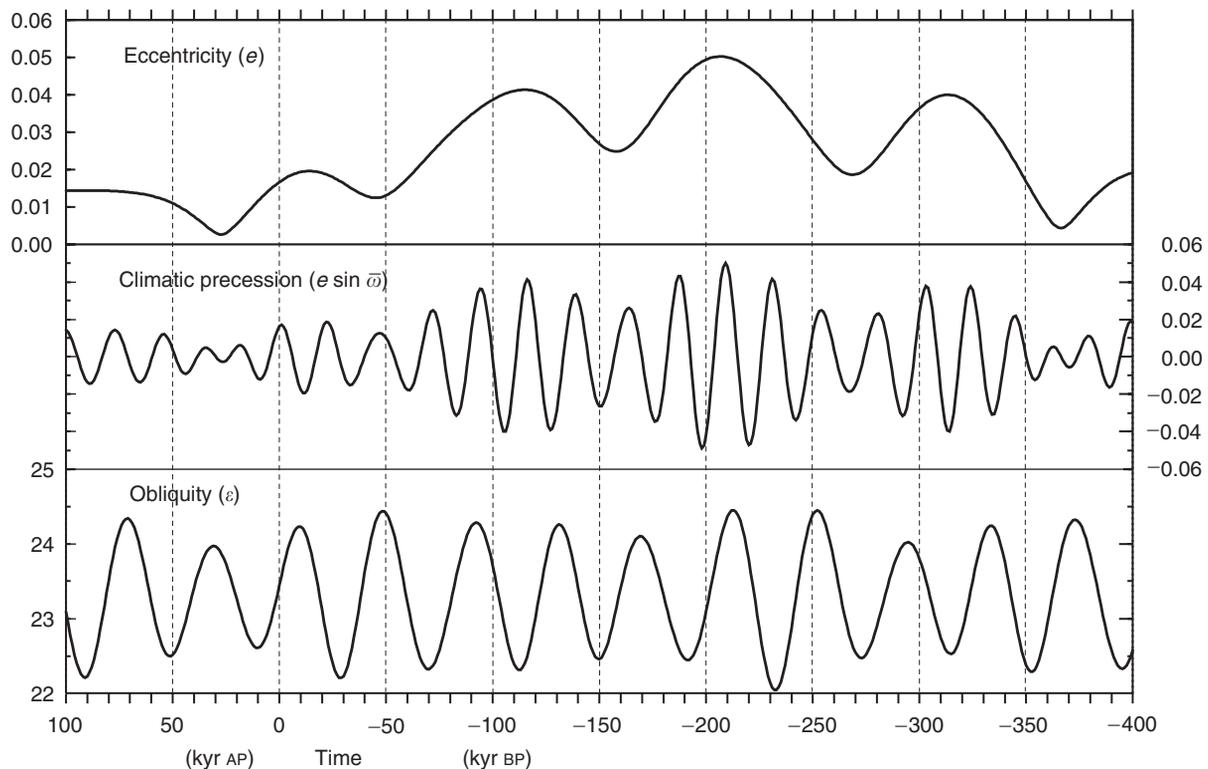


Figure 4 Long-term variations of eccentricity, climatic precession and obliquity from 400 000 years ago to 100 000 years into the future (from Berger).

- For the latitudes where there is a daily sunrise and sunset, i.e., $|\phi| \leq \pi/2 - |\delta|$, W_d is expressed by eqn [5],

$$W_d = S/\pi\rho^{-2}(H_0 \sin \phi \sin \delta + \cos \phi \cos \delta \sin H_0) \quad [5]$$

where H_0 , the absolute value of the hour angle at sunrise and sunset, is given by eqn [6].

$$\cos H_0 = -\tan \phi \tan \delta \quad [6]$$

- For the other latitudes, i.e., $|\phi| > \pi/2 - |\delta|$: Either it is the long polar night ($H_0 = 0$), i.e., $\phi\delta \leq 0$, in which case W_d is given by [7]

$$W_d = 0 \quad [7]$$

Or it is the long polar day ($H_0 = \pi$), i.e., $\phi\delta > 0$, in which case W_d is given by [8].

$$W_d = S\rho^{-2} \sin \phi \sin \delta \quad [8]$$

The daily irradiation varies through the year as well as according to the latitude. Moreover, it also exhibits long-period variations caused by the secular variations in the elements of the Earth's orbit and rotation.

Some features of the long-term variations in eccentricity, obliquity, and climatic precession can be discerned in the insolation variations. Low values of the eccentricity are mirrored in the small amplitude of the insolation change, such as for the recent past and near future; conversely, large values of e induce large amplitudes of the insolation change, for example, at about 100 ky BP (Figure 2C). Solar radiation is mostly

affected by variations in precession, although the obliquity plays a relatively more important role for high latitudes, mainly in the winter hemisphere. The variations in the obliquity are perceptible in the same way in both hemispheres (Figure 6A), i.e., an increase in the obliquity induces an increase in the insolation during the local summer (March to September in the Northern Hemisphere and September to March in the Southern Hemisphere) and an insolation decrease during local winter. Consequently the seasonal contrast in daily irradiation is reinforced. A change in the climatic precession (Figure 6B) such that the June summer solstice is moving from the perihelion to the aphelion (i.e., close to the present-day situation) induces a decrease of insolation over the whole Earth (Northern and Southern Hemispheres) simultaneously over one half of the year (Northern Hemisphere summer season and Southern Hemisphere winter season, i.e., from March to September). Climatic precession plays an opposite role in both hemispheres. At present, perihelion occurs in early January. This situation favors mild winters and cool summers in the Northern Hemisphere, and cold winters and warm summers in the Southern Hemisphere.

Comparison between changes in the orbital parameters and/or in the solar radiation received by the Earth with geological reconstruction of past climate changes is also used to provide a clock for dating the records. In this case it is assumed that the quasi-periods observed in the data are a direct response to the quasi-periodic variations of the forcing. Consequently the astronomical chronology is directly applied to the geological data, possibly with a time lag.

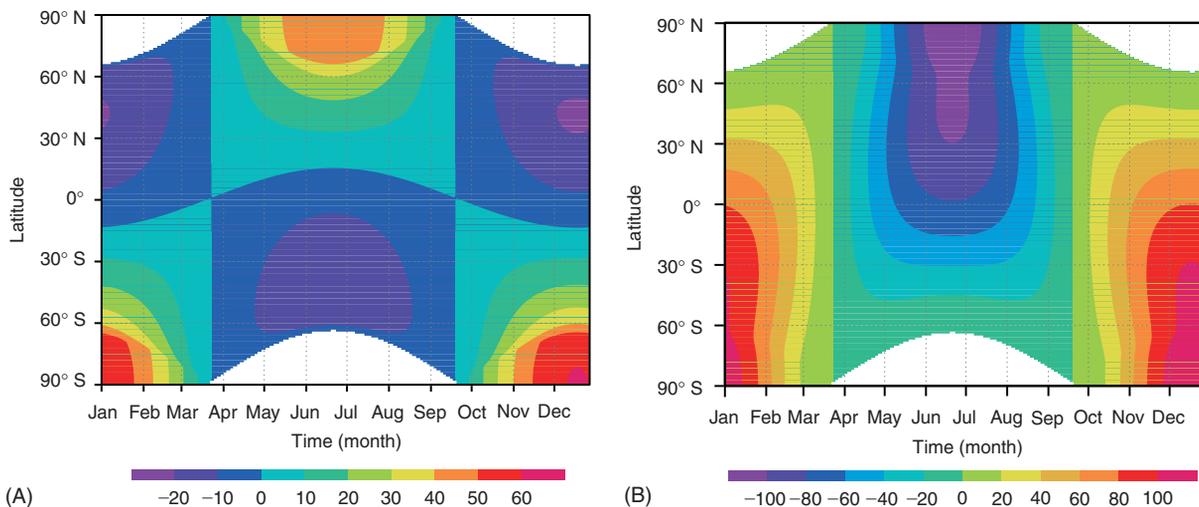


Figure 6 Variation of the seasonal contrast of the mean irradiance ($W m^{-2}$) following (A) an increase of the obliquity from 22.5° to 25° ($e = 0.05$ and winter at perihelion) and (B) a change in the climatic precession (from summer solstice at perihelion to summer solstice at aphelion; $e = 0.05$ and $\epsilon = 25^\circ$).

Paleoclimate Modeling

Climate models are simplifications of reality, designed to describe the complexity of the interactions within the climate system. These numerical climate models can be used to test the astronomical theory of paleoclimate, i.e., to study whether astronomically induced changes in insolation are able to drive the climate system into glacial–interglacial cycles similar to these recorded in geological data. The modeling effort has led to a better understanding of the physical mechanisms involved in the climate system response to the astronomically forced changes in the pattern of incoming solar radiation. Such mechanisms are related, in particular, to the ice sheets, the lithosphere, the hydrological cycle, the cloud properties, the albedo temperature feedback, the land–sea ice temperature gradient, the CO₂ cycle, and the ocean circulation. The different parts of the climate system, i.e., the atmosphere, the hydrosphere, the cryosphere, the biosphere, and the lithosphere, are becoming convincingly modeled separately, and work is going on towards the design of comprehensive coupled models including several parts, if not all of them. A hierarchy of models, climate models of different complexities that differ in their degree of spatial and temporal resolution, are used for paleoclimate purposes.

General Circulation Models (GCMs) are primarily used for simulating geographic features of paleoclimates. Their major limitation is their high computing cost. For this reason they are used for simulations covering a few thousand years at maximum. They provide a ‘snapshot’ view of the climate in equilibrium with the boundary conditions.

At the last interglacial, some 125 ky BP, modeling experiments led to warmer conditions, especially in the high latitudes, reduced sea-ice extent, enhanced northern tropical monsoon and northward displacement of the tundra and taiga biomes, in good agreement with geological reconstruction. However, the strong cooling induced by changes in the orbital parameters at 115 ky BP are not sufficient to initiate glaciation, at least if vegetation changes are not properly taken into account. This clearly puts forward the importance of the vegetation–albedo–temperature feedback. Several GCMs have been used to simulate the climate of the Last Glacial Maximum, some 20 ky ago. Again, important processes at work at that time were identified. They are related to the CO₂ concentration, sea ice, ocean temperature, and land albedo. As part of the Paleoclimate Modeling Intercomparison Project (PMIP), several GCMs performed the same simulation of the mid-Holocene climate (6 ky BP). Some robust features have been identified, for instance

a northward shift of the main regions of monsoon precipitation over Africa and India.

The conceptual models are simple models designed to assess whether a climate process can explain past climate changes. For example, the simple threshold (or multistate) climate model due to Paillard simulates ice volume increase as a function of a smoothed truncation of the insolation. The model distinguishes three distinct states (interglacial, mild glacial, and full glacial) and the transition between them occurs when insolation and ice volume cross prescribed thresholds in insolation and ice volume. This model reproduced reasonably well the succession of glacial–interglacial cycles over the late Pleistocene.

Models of intermediate complexity are the only climate models to be able to simulate the time-dependent behavior of the fully coupled climate system over a time interval long enough to test the astronomical theory of paleoclimate. Earth system Models of Intermediate Complexity (EMICs) include most of the processes described in comprehensive models, in particular the slow-response climate variables such as ice volume, bedrock depression, deep-ocean temperature, and atmospheric concentration of greenhouse gases. They also simulate the interactions between the different parts of the climate system. Moreover, they are simple enough to allow for long-term climate simulations (several glacial–interglacial cycles).

The LLN 2D NH climate model (two-dimensional climate model developed in Louvain-la-Neuve) is one of these EMICs. It was designed in order to understand the response of the climate system to astronomical forcing. It links the atmosphere, the upper mixed layer of the ocean, the sea ice, the continents, the ice sheets, and their underlying lithosphere. It is forced by computed insolation and reconstructed atmospheric CO₂ concentration. It considers only the Northern Hemisphere (the Southern Hemisphere is not considered) and it has no explicit representation of the thermohaline circulation. It has been able to simulate many of the different situations that characterize the last 3 million years: the entrance into glaciation around 2.75 My BP, the dominance of the obliquity cycle during the late Pliocene–early Pleistocene, the emergence of the 100 ky cycle around 900 ky BP, and the glacial–interglacial cycles of the last 600 ky. The climatic changes over the Northern Hemisphere, in particular the continental ice volume, simulated by the LLN 2D NH climate model during the last 400 ky shows a broad good agreement with reconstruction (Figure 7).

However, a major discrepancy in this model is the too frequent melting of the ice sheets during the

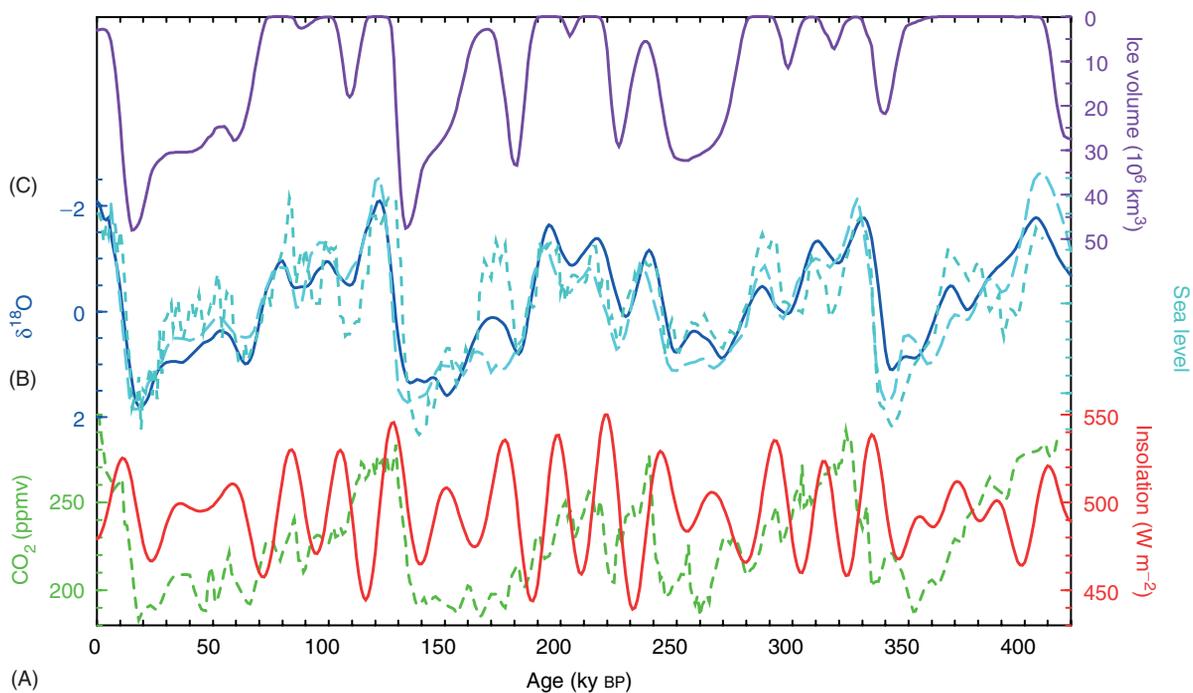


Figure 7 Comparison of records and modeled data over the last 400 000 years. (A) Variation in the mean irradiance in July at 60° N (red full line) and the CO₂ concentration (dashed green line). (B) Proxy records for the variation of continental ice volume, i.e., stacked, smoothed oxygen isotope record as function of age in the SPECMAP time scale (full dark blue line), $\delta^{18}\text{O}$ record from the oceanic core MD900963 (long-dashed blue line), and reconstructed sea level from benthic forams in the oceanic core V19-30 (short-dashed blue line). (C) Northern Hemisphere continental volume as simulated by the LLN 2D NH climate model.

interglacial. The largest difference between the simulated and the reconstructed Northern Hemisphere continental ice volume appears between 180 and 150 ky BP. Moreover an unusual feature shows up between 400 and 350 ky BP. This time interval is characterized by a very long interglacial, which does not seem to be recorded in data. This behavior is possibly caused by the interplay between insolation forcing and CO₂ concentration forcing. This model also confirms that the orbital forcing acts as a pacemaker for the glacial–interglacial cycles and that the climate response to orbital forcing is amplified by CO₂. Moreover, important processes in climate change were identified, such as albedo–temperature feedback, water vapor–temperature feedback, the snow aging process, and the isostatic rebound.

New observation techniques, accurate dating methods, improved transfer functions, and comprehensive climate models will lead to increasingly accurate knowledge of the past evolution of the atmosphere and the oceans, the waxing and waning of the ice sheets, and the growth and retreat of the forests and deserts.

See also

Carbon Dioxide. Climate Variability: Glacial, Interglacial Variations. **Energy Balance Model, Surface. General Circulation:** Models. **Glaciers. Numerical Models:** Methods. **Paleoclimatology:** Ice Cores; Varves.

Further Reading

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