Astronomical theories of climate: a long history

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What have been the characteristic periods of climatic variations over the last few million years? Those responsible for these natural variations are the parameters of the Earth's movement around the Sun: eccentricity of its elliptical trajectory, obliquity and precession of its axis of rotation. How did the astronomers of the 18th century get the intuition of alternating glaciations and interglacial periods? And on what basis did the climatologists of the last century rely to model with a fairly good accuracy the real variations revealed by their geological traces?

1. Astronomical periods in paleoclimatic data

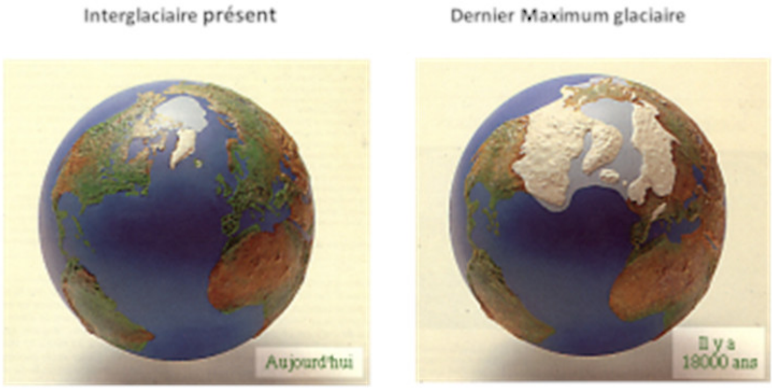


Figure 1. The extent of ice in the northern hemisphere today and at the last glacial maximum [Source: adapted from Joussaume S. ref. [1]].

Reconstructions of atmospheric greenhouse gas concentrations, air temperature in Antarctica, the intensity of the Asian monsoon and the total volume of ice on Earth have highlighted the **glacial-interglacial cycles** that have characterised the climate over the last few million years (Figure 1) [1],[2].

Spectral analysis [3] of these time series [4] reveals **significant periods of** 100,000 years, 41,000 years, 23,000 years and 19,000 years. These periods characterize the long-term variations of three astronomical variables related to the Earth's orbit around the Sun (known as the ecliptic) and its axis of rotation: **eccentricity**, **obliquity** and **climate precession** [5].

1.1. Eccentricity

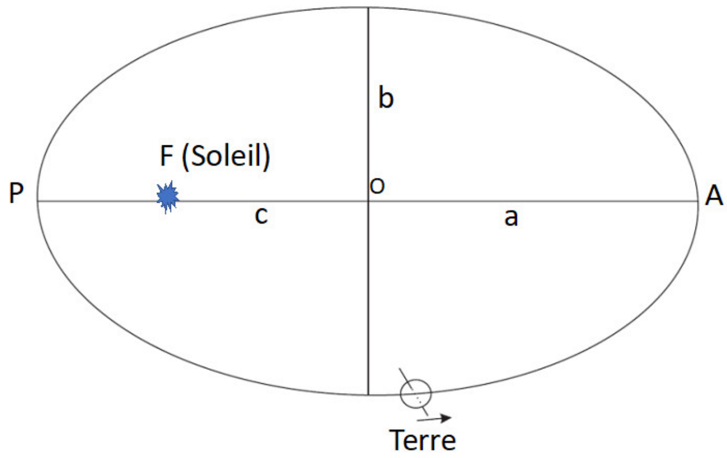


Figure 2. Earth's elliptical orbit around the Sun. O is the center of the ellipse, P the perihelion, A the aphelion, F one of the foci of the ellipse (occupied by the Sun). The distance OF, C, is equal to the product of a and the eccentricity e and is also equal to the square root of (a2-b2). The drawing is not to scale for readability reasons. In reality, the orbit is practically a circle and the sun is very close to its center. [Source: drawing by the authors (A. Berger)]

Eccentricity is a measure of the shape of the orbit which is elliptical according to the first law of Johannes Kepler [6] (1571-1630) from 1609. This shape varies in time from a perfect circle (whose eccentricity is zero) to an **ellipse** which is however very little different from a circle when drawn to scale. This eccentricity is currently 0.016 and has varied over the last few million years between 0 and 0.06. If a *is* the half major axis of the ellipse and b is the semi-minor axis (Figure 2), the eccentricity is defined by $e = \frac{\sqrt{a^2-b^2}}{a}$.

As the semi-major axis is invariant, the variation of the eccentricity is accompanied by the variation of only the semi-minor axis. The latter increases with the decrease of e and ends up being equal to the semi-major axis when the eccentricity cancels. The new semi-minor axis will then decrease with the increase of e until the eccentricity reaches its maximum.

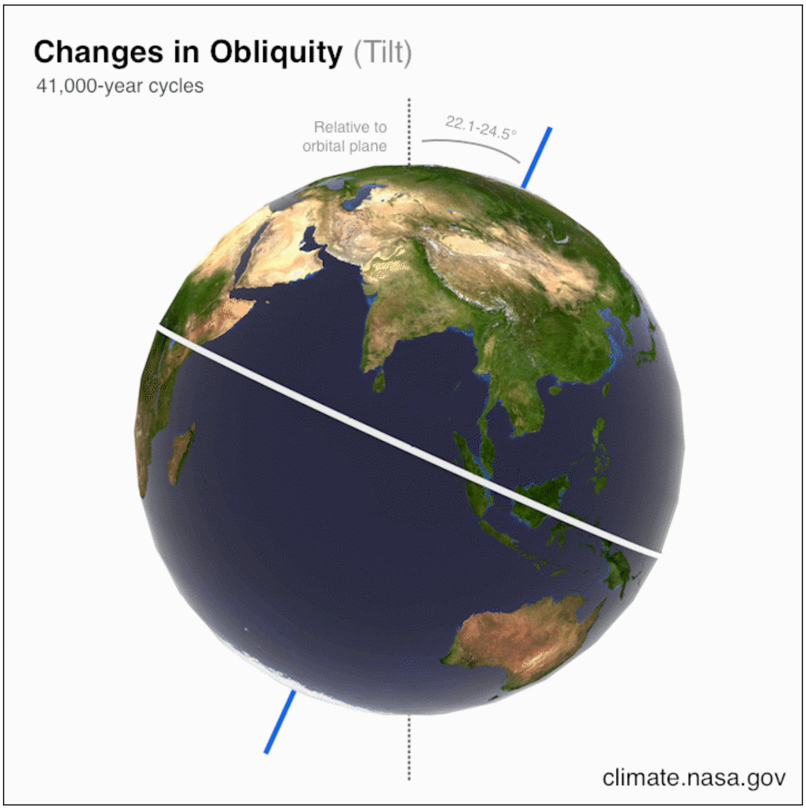


Figure 3. Animation representing changes in obliquity [Source: NASA/JPL-Caltech https://climate.nasa.gov/internal_resources/2000/]

The **variations of *e*** are characterized by multiple periods of which the main one is around 400,000 years and some are close to 100,000 years [2]. Although the Earth's orbit is almost a circle, the difference in the Earth-Sun distance between **perihelion** and **aphelion** [7], relative to the semi-major axis, a, of the orbit is currently 3, 4% (twice the eccentricity). Therefore this same difference for the solar irradiance [8], also called **insolation** [9], is 6.8%.

1.2. The obliquity

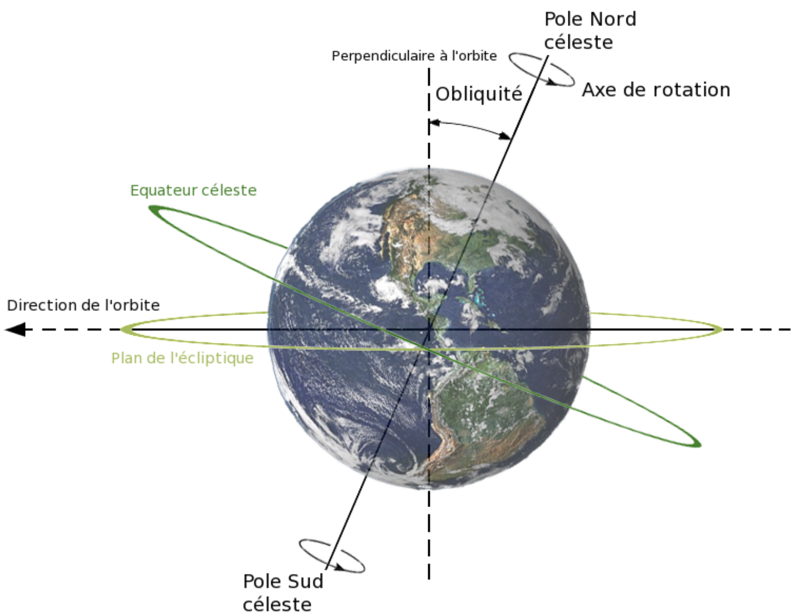


Figure 4. The ecliptic and its relationship to the celestial equator and the Earth's axis of rotation. [Source : derivative work: Daelomin53 (talk)AxialTiltObliquity.png: Dna-webmaster, CC BY 3.0 <https://creativecommons.org/licenses/by/3.0>, via Wikimedia Commons]

The obliquity is the **angle of inclination of the Earth's axis of rotation** to the perpendicular to the plane of the ecliptic. It is currently 23°27' and varies between 22° and 25° with a major period of 41,000 years. It is the obliquity that defines the **tropics**

and the **polar circles** (Figure 3 and 4). It is now decreasing by 46.8'' per century, which explains the displacement of the tropics towards the equator by 1.4 km per century or in an equivalent manner from the polar circles towards the poles. It is this which is at the origin of the seasons.

1.3. Climatic precession

The Earth's axis of rotation currently points to the **NorthStar**, Alpha Ursae Minoris in the **Northern** Hemisphere. This axis, in addition to the variation of its inclination on the perpendicular to the ecliptic plane, moves by forming in space an almost perfect cone whose opening is the obliquity. This movement is that of the **astronomical precession**, a progressive shift in the direction in which the stars are seen (Figures 4, 5 and 6) whose period is 25,760 years. It is associated with the **retrograde** (clockwise) movement of the vernal point on the ecliptic, which is 50.29 arc seconds per year. The latter is in fact defined at the intersection of the equator and the ecliptic (Figure 4).

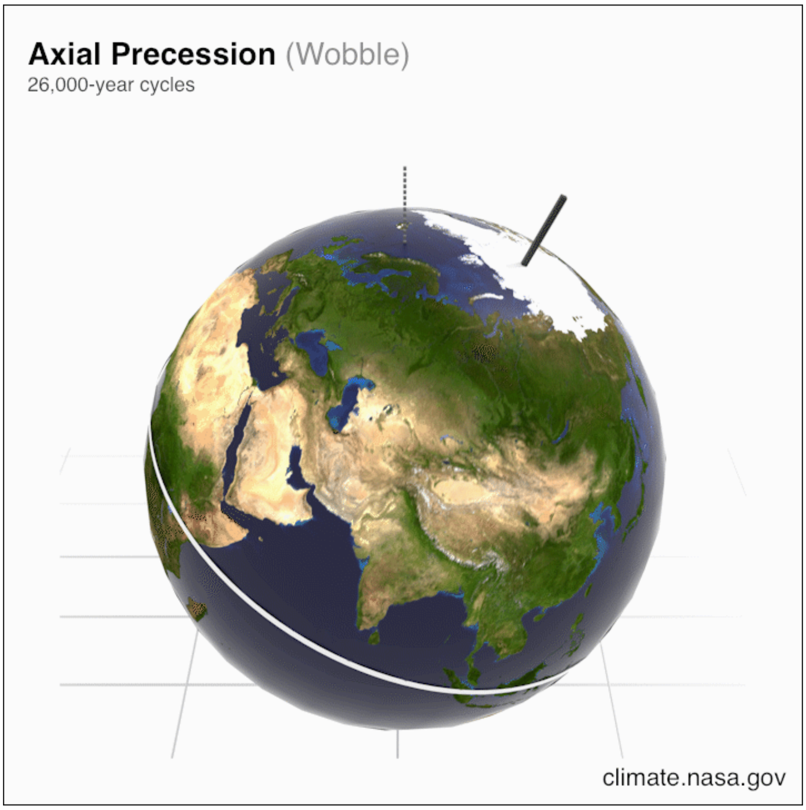


Figure 5. Animation representing the astronomical precession. The clockwise movement shown is that seen from space. It is opposite to the one seen from Earth shown in the following figure. [Source: NASA / JPL-Caltech https://climate.nasa.gov/internal_resources/2001/]

Climate precession is a fundamental parameter in the study of variations in the Earth's climate. It results from astronomical precession and perihelion precession (apsidal precession). It is defined from an **angle** formed between the position of the **perihelion** and the position of the **vernal point** (the direction in which the Sun is seen from the Earth in spring). It thus makes it possible to position the seasons in relation to this perihelion or to calculate the distance from the Earth to the Sun for a particular season. For example, the Earth is currently closest to the Sun at the winter solstice, i.e. during the boreal winter. This variable thus modulates the amplitude of the seasonal variation, currently softening the winters of the northern hemisphere and cooling the summers there.

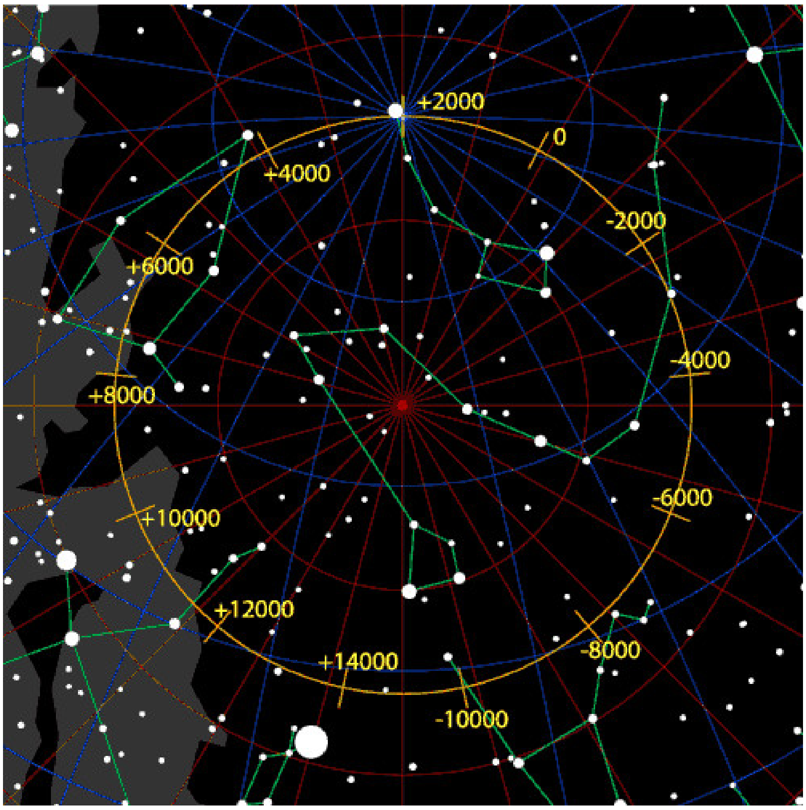


Figure 6. Astronomical precession. Course of the Celestial North Pole in the sky seen from Earth. This view is the one we have of the Earth when we look at the sky. This explains the movement of the vernal point which is counterclockwise, while seen from above the movement is clockwise. The movement schematized here assumes a constant speed of precession and obliquity. [Source: Tau'olunga, CC BY-SA 2.5 <https://creativecommons.org/licenses/by-sa/2.5>, via Wikimedia Commons]

Climate precession varies with an **average period of 21,740 years**. This period is due to the fact that the position of spring and perihelion both change relative to fixed stars in opposite directions. The absolute movement of the vernal point is clockwise and the perihelion is counterclockwise with a period of ~135 200 years. The relative motion of one to the other is therefore approximately as follows $\frac{360}{21740} = \frac{360}{25760} + \frac{360}{135200}$. This average period is in fact the result of the fundamental components which are close to 23,000 years and 19,000 years and which were highlighted in the 1970 [2], thus corroborating the periods found by Hays *et al* [3] in the geological data.

The name climatic precession was introduced [2] because it is the relative position of the vernal point in relation to the perihelion that matters in climatology and not their absolute position in the sky.

The theory that links the long-period variations of these parameters to solar irradiance on the one hand and to climates on the other hand is called the **astronomical theory of paleoclimates** [10],[11]. There are several versions of this theory [12] that we will describe in the context of the history of the discovery of climate variations over the last few centuries.

2. Discovering the great variations in climate

2.1. Evolution of ideas about the evolution of climates since the 18th century

Descriptive discipline, **climatology** has become a multidisciplinary science involving the **five components of** the climate system and their **interactions with** each other:

the atmosphere,

the hydrosphere,

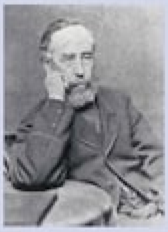
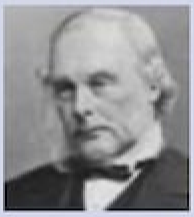
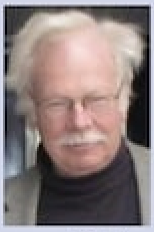
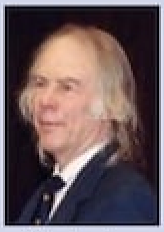
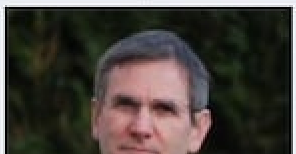
the cryosphere,

the lithosphere,

the biosphere.

Not surprisingly, therefore, the resulting climate varies on scales ranging from seasonal to millions of years. Although this science has literally exploded in recent decades, the discovery and study of the first evidence of climate variation beyond the annual and decadal scales dates back to the 18th century. A synthesis is given in the table below.

Table. Some scientists involved in the evolution of ideas about climate change since the 18th century [13].

Scientists	Prop
 Jens Esmark (1763-1839) Norwegian	The first to pro the Earth orb climate change
Joseph-Alphonse Adhémar (1797-1862) French	Attempt to exp ice ages from equinoxes
 James Croll (1821-1890) Scottish	Introduce the parameters an winter play a fu ice age theory
 Joseph Fourier (1786-1830) French  John Tyndall (1820-1893) Irish  Svante Arrhenius (1859-1927) Swedish	Propose CO_2 va of glacial perio
 Joseph John Murphy (1827-1894) Irish	Introduce the summer in the is at the basis o
 Milutin Milankovitch (1879-1958) Serbian- Croatian	Popularize the introduce a variations base elements and Murphy that c important role
 James D Hays (1933-) American  John Imbrie (1925-2016) American  Nicholas Shackleton (1937-2006) English  Cesare Emiliani (1922-1995) American	Improve decis for paleoclim Hays, Imbrie famous for the published in Sc
 	Introduce res (Berger) and astronomical s

2.2. A first step: glacier extension and climate change

Figure 7. Example of an erratic block transported from Savoie to the Lyon region (St-Fons). [Source: Tusco, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons]

It was in the 18th century that the existence of erratic blocks in the mountainous landscape (Figure 7) was first associated with the **spectacular extension of glaciers**. In 1744, the Grenoble geographer Pierre Martel [14] (1706-1767) reported that the inhabitants of the Chamonix valley in the Alps of Savoy attributed the dispersion of these roches moutonnées to the glaciers themselves, whose extension would have been much greater in the past. This idea was **revolutionary**, because until then most scientists still referred to the myth of the Flood in the Bible to explain the structure of landscapes. This was the case of the Geneva-based Horace Bénédicte de Saussure (1740-1799), the French paleontologist George Cuvier (1769-1832) and the Scottish geologist Charles Lyell (1797-1875), who all continued to assume that these blocks were carried by the violence of the waters.

However, the location and nature of these blocks and other moraines led some scientists to admit that **transport through ice** would better explain the various observations. The Scottish naturalist James Hutton (1726-1797) was the first to support this idea. Others followed and discovered the imprint of climate change in the fluctuating extent of glaciers: the Swiss engineer Ignace Venetz (1788-1859), the German forest engineer Albrecht Reinhart Benhardi (1797-1849), the Swiss geologist Jean de Charpentier (1786-1855) and the German botanist Karl Fredrich Schimper (1803-1867), who introduced the notion of an ice age. However, it was the Danish-Norwegian geologist Jens Esmark (1763-1839) who, in 1824, continuing his analysis of glacier transport, proposed, most probably for the first time, that **climate change** was the cause of the ice age and that it was due above all to **variations in the Earth's orbit**.

It was the work of these precursors that led the Swiss geologist Louis Agassiz (1801-1873) to formulate his address to the Swiss Natural Science Society in Neufchâtel in 1837 *on Upon glaciers, moraines and erratic blocks*. This address was criticized, however, because it appeared that Agassiz had "borrowed" his conception of glacial theory from his former university colleague Schimper and had failed to recognize Charpentier's original contribution that introduced him to glacier research.

2.3 The Birth of the Astronomical Theory of Paleoclimates

It was also at the beginning of the 19th century that the Frenchman Joseph Adhémar (1797-1862), not content to study the polar ice caps, tried to explain in his book "Révolutions de la mer, déluges périodiques" [15] the **recurrence of the ice ages from the precession of the equinoxes**. The astronomical theory of paleoclimates was born and could be continued thanks to the development of celestial mechanics with the Frenchmen Jean le Rond d'Alembert (1717-1783), Jean-Baptiste Joseph Delambre (1749-1822), Pierre Simon de Laplace (1749-1827), Louis Benjamin Francoeur (1773-1849) and Urbain Le Verrier (1811-1877). At the same time, a further step was to be taken with the first calculations of the **long-term variations in the energy received from the Sun**, variations due to the eccentricity of the Earth's orbit, the precession of the equinoxes and the obliquity of the ecliptic. Thus illustrating the following scientists: John Frederick William Herschel (1792-1871), L.W. Meech (1821-1912) and Chr. Wiener (1826-1896), to whom we can associate the mathematicians André-Marie Legendre (1751-1833) and Simon-Denis Poisson (1781-1840).

Everything was now ready for the Scotsman James Croll (1821-1890) to develop a **theory of the ice ages** based on the combined effect of the **three astronomical parameters**, a theory according to which the **winter of the northern hemisphere** was to play a decisive role. This theory was greatly appreciated by the naturalist Charles Robert Darwin (1809-1882) and taken up by the Scottish geological brothers Archibald (1835-1924) and James (1839-1914) Geikie who introduced the notion of **interglacials**. It is also the basis for the classification of alpine glaciations by Albrecht Penck (1858-1945) and Edouard Brückner (1862-1927) and of the American ones by Thomas Chowder Chamberlin (1843-1928). However, geologists were becoming increasingly dissatisfied with Croll's theory and many criticisms were made.

Many refuted the astronomical theory and preferred explanations related to the planet Earth alone. The Scottish geologist Charles Lyell (1797-1875) emphasized the geographical distribution of land and sea to explain the alternation of hot and cold climates, while others turned to variations in the concentration of certain gases in the atmosphere [16]. Thus, the French physicist Joseph Fourier (1786-1830) put forward the original idea of the **greenhouse effect theory** related to the concentration of **carbon dioxide** in the air. He was followed by the Irish chemist John Tyndall (1820-1893), who was responsible for the first experiments on the absorption of infrared radiation and the hypothesis of the fundamental role played by water vapour in the greenhouse effect. Later, the Italian Luigi de Marchi (1857-1937) and the Swedish chemist Svante Arrhenius (1859-1927) proposed, along with other scientists of their time, that **ice ages** were due to decreases in atmospheric carbon dioxide. In 1895, Arrhenius suggested in an article published at the *Stockholm Physical Society* that a 40% reduction or increase in the concentration of CO_2 in the atmosphere could generate **feedback** processes that would explain glacial advances and retreats (See **From the discovery of the greenhouse effect to the IPCC**).

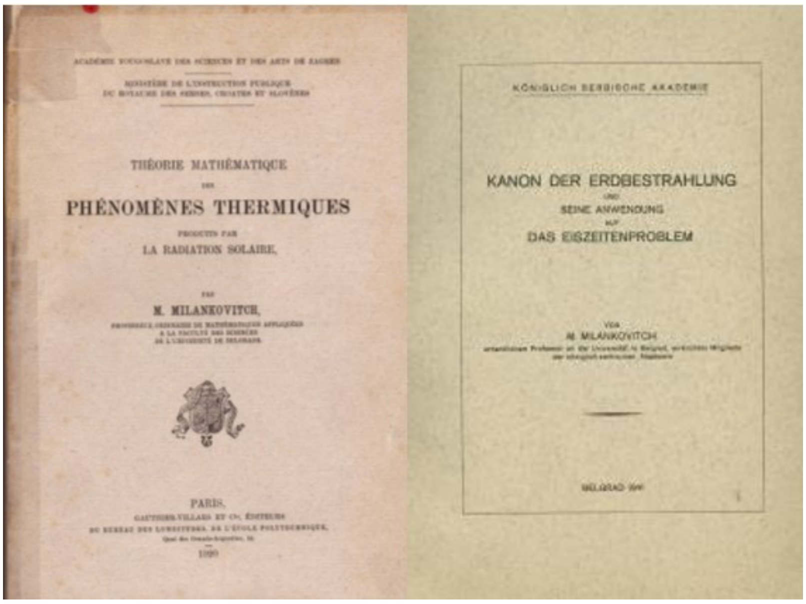


Figure 8. Covers of the two books by Milankovitch. [Source: © Photo by André Berger]

A rebirth of astronomical theory would however be possible with the improvements made to the calculation of astronomical elements by the American astronomer John Nelson Stockwell (1832-1920) and in 1904 to that of solar irradiation by the German mathematician Ludwig Pilgrim (1879-1935). However, it is Joseph John Murphy (1827-1894) who, as early as 1869, was responsible for the fundamental hypothesis that the **cool summers of the northern hemisphere were the basis for the existence of the ice ages**. This original idea was taken up in 1921 by the Austrian climatologist Rudolf Spitaler (1859-1946), but was popularized by the Serbian geophysicist Milutin Milankovitch (1879-1958) (Figure 9), mainly through his books "*Théorie mathématique des Phénomènes thermiques produits par la Radiation solaire*" [17] (1920) and "*Kanon der Erdbestrahlung und seine Anwendung auf des Eizeitenproblem*" [5] (1941) (Figure 8).

Milankovitch was a contemporary of the geophysicist and meteorologist Alfred Wegener (1880-1930), whom he met through the Russian-German climatologist Vladimir Köppen (1846-1940). The latter had heard of Milankovitch's work and his daughter, Elsa Köppen, had married Wegener. The modern era of the astronomical theory was born, although the **lack of reliable paleoclimatic data** and a **reliable time scale** were at the basis of many criticisms from the world of both geologists and meteorologists.

It was not until the 1950s and 1960s that new techniques made it possible to date, measure and interpret climate records in marine sediments, ice and on the continents.

In 1955, the American Cesare Emiliani [18] proposed a stratigraphy, still in force, based on the succession of minima and maxima of the **oxygen-18/oxygen-16 isotope ratio** measured in the shells of foraminifera found in the sediments of the deep ocean. The interpretation of this isotopic ratio was to follow in terms of salinity with Jean-Claude Duplessy [19] and in terms of temperature and ice volume with Nicholas Shackleton and Niels Opdyke [20].

Mathematical tools then made it possible to create transfer functions to quantitatively interpret the information collected in the oceans or from tree rings. The effort of the CLIMAP group [21] (1976) resulted in the **first seasonal climate map of the Last Glacial Maximum** and the seminal 1976 paper by James Hays, John Imbrie (1925-2016) and Nicholas Shackleton (1937-2006). The advent of large computers made possible the first climate simulations based on general circulation models [22] and the continuation of astronomical calculations led to a highly accurate reference time scale and the determination of daily and seasonal irradiation, which was essential for climate modeling [23].

3. Milankovitch's astronomical theory and afterwards

3.1. Milankovitch and the cycles of glaciation

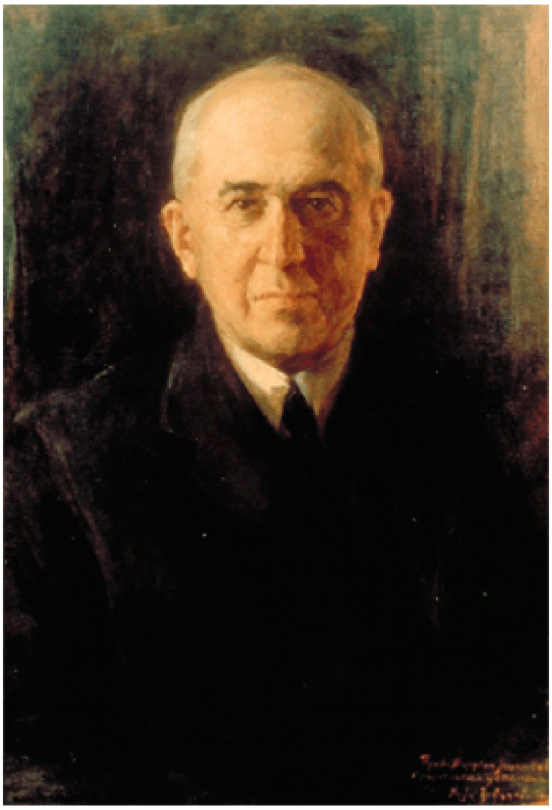


Figure 9. Portrait of Milutin Milankovich at the Serbian Academy of Sciences and Arts in Belgrade, painted by Paja Jovanovic in 1943 [Source: frwiki, (CC BY-SA 3.0), https://fracademic.com/dic.nsf/frwiki/1167469]

Milutin Milankovich (Figure 9) was born in 1879 in Dalj (in Austro-Hungary at that time, now in Croatia) and died in Belgrade in 1958. He obtained his degree in Civil Engineering at the University of Vienna in 1902 and his doctorate in science in 1904. He then began a career as a construction engineer, where he enjoyed a great reputation for his dams, bridges and other industrial halls. He was appointed professor at the University of Belgrade in 1909 and taught celestial mechanics and theoretical physics there for 46 years. In 1912, he decided to devote himself to the mathematical study of climate. Although, as stated earlier, Milankovitch was not the first to have developed an **astronomical theory** explaining the recurrence of the ice ages, he nevertheless contributed to its **popularization** in a masterful manner. He first devoted himself to the search for the best values available at that time to calculate long-term variations in **eccentricity**, **obliquity** and **climatic precession**. Thus, in his 1920 book, he used Stockwell's 1873 and Pilgrim's 1904 values. In his book of 1941, he decided with his colleague, the Serbian astronomer Miskovitch (1892-1976), to use the values of Le Verrier of 1855, but after having corrected them to take into account the best values of the masses of the planets that had become available in the meantime.

Its insolation curve for the boreal summer at 65°N, based on Murphy's idea and calculated from the work of Le Verrier and Miskovitch, has remained famous (Figure 10), as it allowed geologists, Brückner, Köppen and Wegener (1925) in particular, to interpret the **glacial-interglacial cycles** as they knew them at that time.

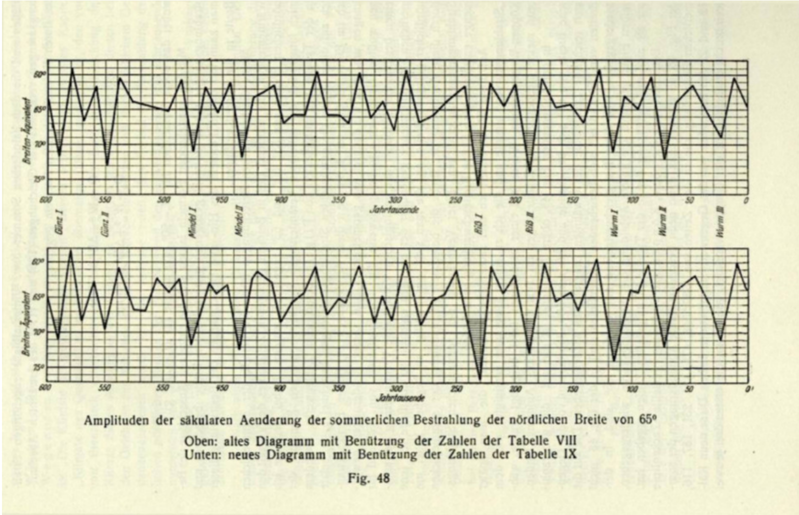


Figure 10. Long term variations of the equivalent latitude of 65 ° N over the last 600,000 years beginning in 1800 AD as in Le Verrier. [Source: Extract from the book by Milankovitch [5]]

In this Figure 10, the top curve is based on summer heat insolation calculated from the astronomical values of Stockwell and Pilgrim, while the bottom curve is based on summer heat insolation calculated from astronomical values of Le Verrier and Miskovic. Both figures show the current latitude, called the equivalent latitude, which receives the same amount of energy during the **caloric summer** of the northern hemisphere as 65 ° N latitude during the same season in the past. For example, 22,000 years ago, latitude 65 ° N received 426 caloric units less than it does today, that is, 13,455 caloric units minus 426 which gives 13,029 caloric units, at pretty much what the latitude 70 ° N currently receives (13 074). **The caloric unit is a quantity introduced by Milankovich such that the solar constant serves as the unit of radiation and that the unit of time is the 100,000th part of the year.** Caloric summer is exactly half a year comprising all days that receive the greatest radiance. In other words, any day in the caloric summer of one hemisphere receives greater energy than any day in the caloric winter of the same hemisphere.

Milankovitch does not seem to have been interested in the periods which characterize the long-term variations of these astronomical parameters and simply notes, as Emiliani (1922-1995) will do in 1955 [12], [19], that the average distances between the successive maxima of his curves are for the eccentricity 92,000 years, for the obliquity 40,000 years and for the precession 21,000 years. He was also not interested in their analytical developments. In fact, it was only at the end of Milankovich's life that the first solutions appeared allowing a more precise calculation of the astronomical elements.

3.2. More precise calculation of astronomical elements

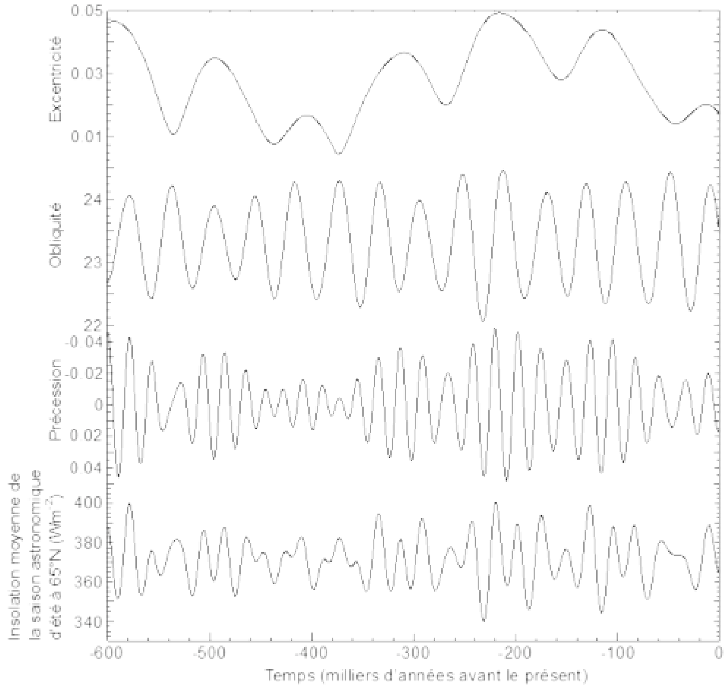


Figure 11. Long-term variations over the last 600,000 years in the eccentricity, climate precession, obliquity and mean insolation received at 65°N during the astronomical half-year summer season of the Northern Hemisphere. [Source: Figure drawn by the authors from references 29 and 30]

These were first those of the Dutch-born American astronomers Dirk Brouwer (1902-1966) and A.J. Jos van Woerkom (1915-1991) in 1950, of the Russian geophysicists S.G. Sharaf and N.A. Budnikova in 1967 and of the French astronomer Pierre Bretagnon [24] (1942-2002) in 1974.

It was then that André Berger published the **trigonometric series** which directly provides the spectrum of long-term variations in eccentricity, obliquity and precession, and allows a simple but precise calculation of the numerical values of these parameters over the last millions of years [25], [2]. The **geological data** becoming more and more reliable over the last millions and tens of millions of years have made it possible to calibrate the solutions of Jacques Laskar [26] who was the first to calculate the values of the three astronomical parameters over very long periods of time and with such precision [27]. Studies of the sensitivity of the astronomical periods to variations in the Earth's rotation speed, the Earth-Moon distance and the dynamic ellipticity of the Earth finally showed a progressive decrease of these periods over several hundreds of millions of years [28].

The quality of the calculation of the parameters of the Earth's orbit and its rotation achieved over the last few decades makes it possible to reproduce **long-term variations** in eccentricity, obliquity and climatic precession with **excellent accuracy**. These parameters [29] can then be used to calculate the solar energy arriving on Earth, for example during the astronomical season of a half-year of the Northern Hemisphere summer at 65°N [30]. Variations are given in Figure 11 for the last 600,000 years so that they can be compared with similar variations described by Milankovitch (Figure 10). This comparison makes it possible to assess the quality of the Milankovitch curve obtained a hundred years ago and representing the same energy available in summer at 65°N. But it also highlights the improvement of the time scale and shows a finer structure of the variations.

As mentioned above, it was the Irishman Joseph John Murphy who first proposed in 1869 that **a long, cool summer and a short, mild winter** would be the most favourable conditions for entering the **ice age**. Milankovitch popularized and propagated the idea by considering insolation at 65°N. This idea of considering high boreal latitudes stems from his work on the influence of snowfields, ice and ice caps on climate. It is in these polar latitudes of the northern hemisphere that one finds vast continental expanses allowing the installation of immense ice sheets with significant positive feedbacks allowing a significant intensification of the insolation forcing. Figure 11 suggests that periodic variations in astronomical parameters are at the origin of **cyclical climate variations in the past** (astronomical theory of climate). In particular, the cyclicity of the 100,000-year ice ages of the last hundreds of thousands of years [4] is correlated with eccentricity.

4. Messages to remember

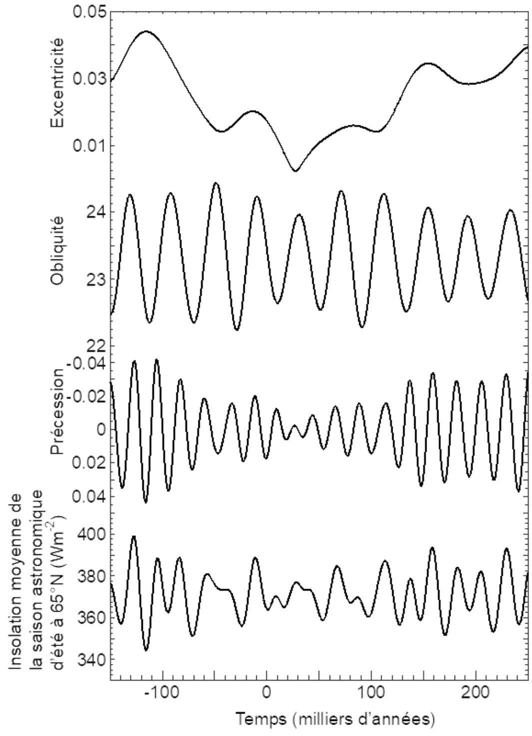


Figure 12. Variations in astronomical parameters between 150,000 years in the past and 250,000 years in the future. Figure drawn by the authors from references 29 and 30]

The **astronomical theory of paleoclimates** and its various versions have unquestionably helped to understand the climatic variations of the last millions of years and, in particular, the recurrence of glacial-interglacial cycles of the Quaternary [31].

The parameters of the **Earth's motion around the Sun** (eccentricity of its elliptical trajectory, obliquity and precession of its axis of rotation) are responsible for the **natural climatic variations** in the last millions of years.

This adventure began more than three centuries ago. It has made it possible to progressively clarify the framework within which the current climate varies and thus to better define **the possible impact of human activities on the climate of** the coming millennia [32]. Figure 12 reproduces the variations in astronomical parameters between 150,000 years in the past and 250,000 years in the future. Note that over the next 50,000 years, obliquity, but especially eccentricity, will decrease, with the Earth's orbit becoming circular in about 27,000 years. This has a direct impact on climate precession, which varies very little over the next tens of thousands of years. This **stability** is visibly reflected in the evolution of insolation with a possible impact on the climate, as other forcings, such as **greenhouse gases**, could then exert a **greater influence** on the climate.

Notes and References

Cover image : Sequence of loess-paleosol near Xian, Shaanxi Province, China. The red layer in the middle of the picture corresponds to the interglacial MIS-9, 330 000 years ago (source: authors)

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[7] Perihelion and aphelion are the places in the Earth's orbit around the Sun where the Earth-Sun distance is the shortest and the longest respectively. If rp is the distance to perihelion and r_a to aphelion, the ellipse equation gives $r_p = a(1-e)$, $r_a = a(1+e)$ et $r_a - r_p = 2ae$.

[8] Irradiance is expressed in Watts per m^2, it is the quantity of energy, in Joules, which passes per unit of time, the second, perpendicularly through a unit of surface, one m^2 and this, at the average distance Earth-Sun.

[9] The word insolation is an abbreviation for *incoming solar radiation*.

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