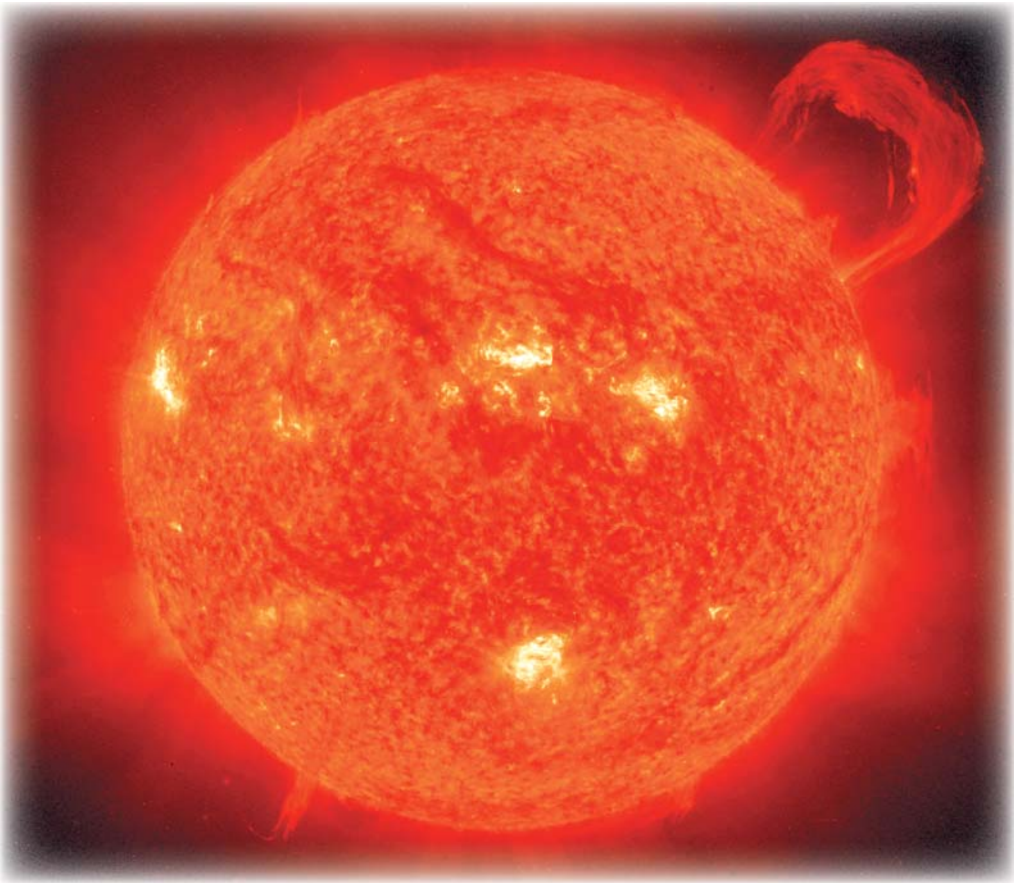
Three roundabouts, summer and an ice age

Climate variations on a long time scale such as ice ages, which come and go, can be linked to variations in the Earth's movement around the Sun. Such natural climate variations set the scene for understanding the climate from a human perspective.



Energy from the Sun is a driving force behind Earth's climate and variations in Earth's orbit around the Sun are believed to be the cause of major climatic events such as ice ages.

By Bjarne Siewertsen

Climate change is not strange viewed on sufficiently long term. Rather, we could from a longer perspective wonder why the climate has not changed more than it has. The climatic processes have never gone berserk in a way which made it totally impossible to sustain life on earth, such as transforming Earth into an uninhabitable, frozen planet or a barren wasteland without water.

The long term climate changes may in themselves seem very dramatic from a human perspective. Within the past one million years the norm in our part of the world has been a colder and much more inhospitable climate than we know today. The climate has alternated between long ice ages, which have covered much of Europe and North America in ice, interrupted by relatively warm and short interglacial periods.

Today we are experiencing one of these interglacial periods, and to put current concerns about global warming in perspective, one could ask whether we are actually at the dawn of a new ice age and thus faced by challenges of an entirely different magnitude? For those concerned about that downloading the latest *IPCC assessment report* (the AR4 released in 2007) must be comforting. The report states it as *very unlikely* that a naturally caused ice age will commence on Earth within the next 30 thousand years.

In order to understand short term climate development, we need to understand how the current climate situation fits into the larger context, which in recent geologic ages have seen ice ages come and go.

What exactly triggers and

ends an ice age is still open to debate, but most scientists agree that one answer lies in the cyclical variations of Earth's movement around the Sun.

These variations are collectively known as the Milankovitch cycles after the Yugoslav geophysicist Milutin Milanković (see box).

The shape of the Earth's orbit

Earth moves around the Sun in an elliptic orbit. How much the ellipse departs from circularity is known as the eccentricity of the ellipse and varies over time due to the gravitational pull of the other planets in the Solar system (see box). This variation is cyclical with the orbit going from being almost circular to its maximum eccentricity and back again, over a term of 95,800 years.

The point of the orbit where Earth has the greatest distance to the Sun is called the aphelion, while the perihelion corresponds to the point where the distance is the least. Presently perihelion occurs around January 3rd when Earth's distance to the Sun is around 146 million kilometers, while aphelion is around July 4th and we are 151 million kilometers away from the Sun.

When the movement around the Sun achieves its greatest circularity, the distance to the Sun at aphelion and perihelion is almost identical, and when the ellipse has maximum eccentricity, the solar irradiance between aphelion and perihelion varies by as much as 30 percent.

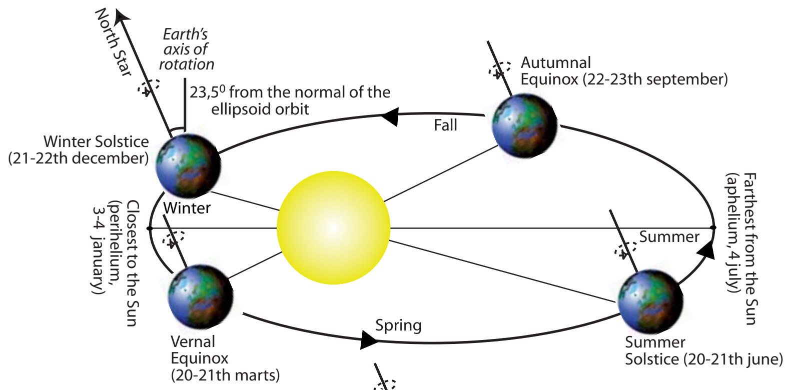
Current solar irradiance is seven percent lower in June than in December.

The Earth's axial tilt

Earth does not revolve just around the Sun. In a day it completes a rotation around itself. But the Earth axis of rotation is not perpendicular to the plane of its orbit. The tilt is currently 23.44 °, but varies cyclically from 21.39 ° to 24.36 ° and back on a term of 41,000 years. The second cycle is called the inclination (see box).

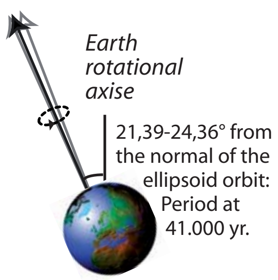
Eccentricity and inclination

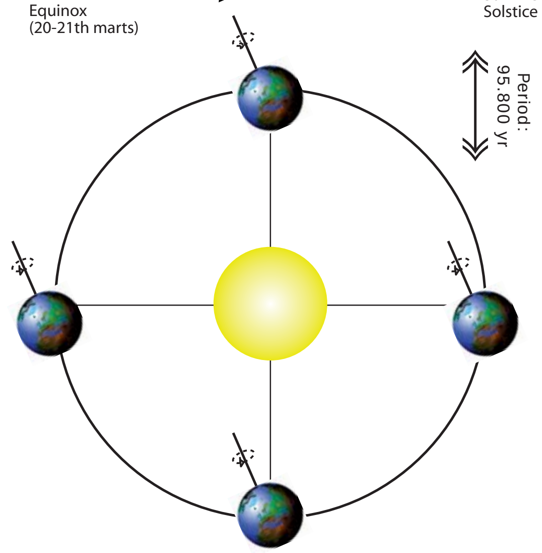
Earth moves around the Sun in an elliptic orbit. Earth's orbit around the Sun varies from being nearly circular to moderately elliptical. Going through a cycle from a circle to an elliptical orbit with maximum eccentricity and back again requires a term of approx. 100,000 year. →



The Earth's axial tilt

Earth's axis of rotation in relation to its orbit varies between 21.39 and 24.36 degrees. This cycle is called the inclination and has a term of approx. 41,000 years. ↓





Graphics: Bjarne Siewertsen, 2007

Croll og Milankovitch

The idea that Earth's movement around the Sun and around itself could have a cyclical effect on Earth's climate is now old news. It was first proposed by the Scottish naturalist James Croll (1821 - 1890) in the late nineteenth century.

Croll said that the best conditions for the spread of ice sheets occurs when winters are coldest, i.e. those winters when Earth is farthest from the Sun in a highly eccentric orbit. However, he could not get his calculations for the beginning and ending of ice ages to fit with the geological evidence, which piled up at the turn of the century, and his theory was discredited.

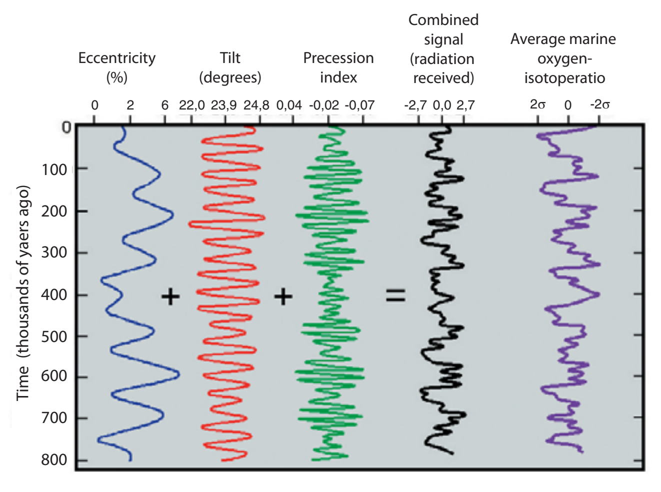
In the early twentieth century, however, the theory was adopted and further developed by the Yugoslav geophysicist Milutin Milanković (1879-1958) who, with the German climatologist Wladimir Peter Köppen (1846-1940), figured out where Croll's error lay. The two proposed that cool summers were decisive in triggering an ice age, since during a cold summer the melting of polar ice caps did not outweigh the accumulation of ice during winter.

Milanković and Köppen maintained that it had to be the summer irradiation on the northern hemisphere, which was the determining factor. Only in the northern hemisphere do the land masses such permit the build up of continental ice sheets.

Milanković's great achievement was that he subsequently calculated the variation of irradiation as a function of season and latitude over the last one million years, which he did by hand. It took him 20 years, and in 1941 he published a 633-page book titled "Canon of Insolation of the Earth and Its Application to the Problem of the Ice Ages".

Milanković never had the chance to see the geological evidence for these cycles. In 1976, the marine geologists Jim Hays, John Imbrie and geophysicist Nick Shakleton succeeded in demonstrating that glaciations closely correspond to 100,000, 41,000 and 22,000 year cycles, by studying oxygen isotopes in deep sea sediments, dating more than 300,000 years back in time.

Hays, Imbrie and Shakleton examined the hard parts of calcareous invertebrates, which constitute the bottom sediments and traced an oxygen-isotope composition of chalk, which showed these glacial cycles. The fact is that oxygen-isotopic composition in both the ice and in the limestone varies according to how much or little ^{18}O, is bound in ice sheets.



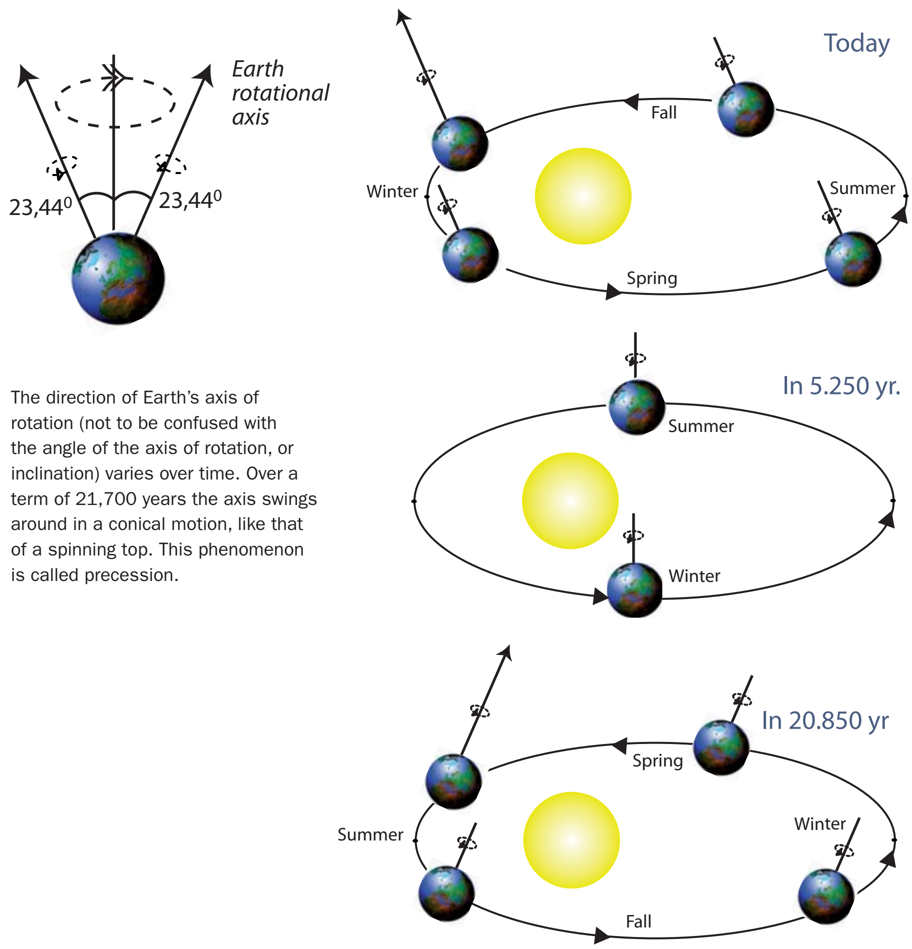
The graph shows the cumulative effect of the three Milankovitch cycles (eccentricity, inclination and precession) as variations in the amount of radiation the Earth receives from the Sun. To the right is a curve of the oxygen isotope relation O^{18}/O^{16} as measured in the cores of marine sediments. This ratio is indirect evidence of temperature.

The less the tilt is, the less is the difference between summer and winter. If the angle was 0° and the axis of rotation was perpendicular to the plane of its orbit, the daily solar irradiation would remain constant throughout the year on any one location on Earth (except for the variations due to eccentricity).

Conversely, a steeper slope will result in an extension of the period of polar nights.

Changes in the axial tilt have great impact on the length of the days (direct solar irradiation) at high latitudes during summer. A small tilt will contribute to the build up of extensive ice sheets, while a greater angle of tilt would increase the melt from the ice sheets.

Precession



The direction of Earth's axis of rotation (not to be confused with the angle of the axis of rotation, or inclination) varies over time. Over a term of 21,700 years the axis swings around in a conical motion, like that of a spinning top. This phenomenon is called precession.

Graphics: Bjarne Siewertsen, 2007

The direction of the Earth's axis

Direction (in this case not the angle) of Earth's axis of rotation also changes cyclically. Over a term of 21,700 years the axis swings around in a conical motion, like a spinning top (see figure). During this period, it changes direction, but not tilt, so that in 10,500 years summer will occur when Earth is closest to the Sun. This will make summers warmer than they are now, but also shorter. This third cycle is called precession.

According to Kepler's 2nd law a line joining a planet and the Sun sweeps out equal areas during equal intervals of time. Thus, currently winters (which are closer to the Sun than the summer) are shorter than summers. Similarly, summers will be shorter than winters in some 10,500 years.

However, conditions will be completely opposite in the southern hemisphere.

When summer is replaced by an ice age

As we have seen summer and winter are the product of inclination. But what about larger climatic events such as the coming and going of ice ages? This matter is somewhat more complicated.

The combined effects of eccentricity, inclination and precession, create very complex irradiation variations along Earth's latitudes (see figure).

Large ice sheets began to develop 2.75 million years ago on the northern hemisphere. Ice sheets built up and melted within a 41,000 year term (and singular incidents every 22,000 years) or in other words according to Earth's inclination. This trend continued while the temperature in general decreased on the northern hemisphere.

The cooling and the impact of the inclination cycle were predominant until some 900,000 years ago, when a threshold apparently was reached and the ice caps no longer melted away after the inclination cycles. Thus the

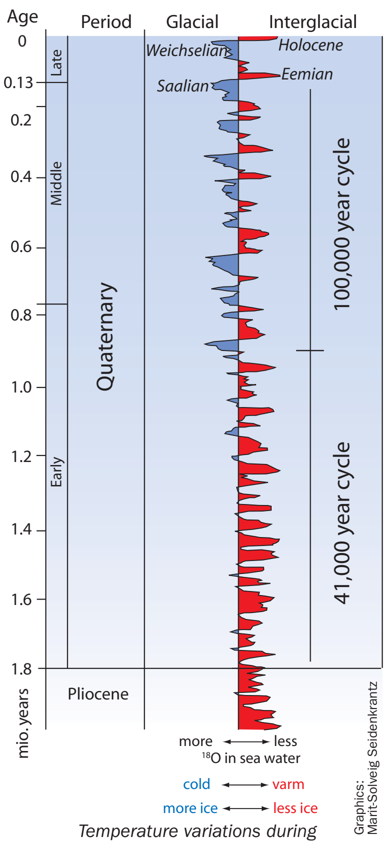
Mapping of the climate of the past

Knowledge of the climate of the past is important in order to understand today's climate. While charting present climate can be done by measuring important parameters such as temperature and precipitation, one must resort to indirect evidence when determining the climatic conditions in geological history. Such geological evidence of climatic conditions can for instance be the geographical distribution of geological deposits, which point to a warm climate such as deposits of coal, salt and sediments typical of deserts - or to a cold climate such as glacial deposits. In these deposits, there will often be remnants of past flora and fauna, which can also tell scientists whether it had been cold or hot at that time and place.

When examining these sediments one must naturally take into account that the continents have shifted over time, it is therefore possible to find depositions originating from tropical conditions in the Arctic underground.

You could say that the closer you come to the present date, the better the geological evidence of climate variability is – this is in part because of the accessibility of deposits of recent date, which are relatively more common and because in terms of land mass displacement there are fewer sources of error. Finally, it is also possible to make more accurate dating of newer sediments, because there are more dating techniques available when the deposits are more recent. In the last decades, interest has especially turned towards ice core drilling in Greenland and Antarctica, since it is possible to interpret climate variability on a yearly basis several hundred thousand years back in time. One of the main methods for reconstruct the temperature of the past is by measuring the amount of the oxygen isotope 16O (which is the general oxygen isotope, and represents over 99% of the oxygen on Earth) and its heavier – and rarer counterpart – 18O. Since the light oxygen isotope ^{16}O evaporates more easily than ^{18}O, there will be less of the heavy isotope present in the atmosphere during cold periods than in warm periods. The colder the atmosphere at a given time, the less ^{18}O will therefore be present in the precipitation as well. In the ice sheets, the relative volume of the two oxygen isotopes reflects the atmospheric temperature at the time the layer was formed.

Calcareous organisms such as mussels and coral also accumulate oxygen isotopes in their shells while alive. Therefore, analysis of the chemical composition of the hard parts of calcareous organisms also tells scientists about the temperature conditions, while the organisms lived.



Temperature variations during 1.8 millions years.

eccentricity began to take control of the climate and ice ages have since then occurred with 100,000 year intervals. In addition to the 100,000 year cycle the lesser 40,000 and 20,000 years cycles manifest themselves as shorter cold spells.

Scientists generally agree that the Milankovitch-extremes can trigger ice ages under various conditions. But there is also consensus that something more is required. The Milankovitch cycles interact with the quantity of dust and other particles in the atmosphere, as well as the relation between the continents and how ocean currents affect the climate system and change rainfall patterns.

A cornerstone of our understanding

There are several small blanks that have not been included in the above, since they are not central to an understanding of the mechanics of the Milankovitch cycles. Earth, for instance, does not behave quite like the spherical body, as assumed in Kepler's laws, and we have not looked in depth upon the gravitational effect of the other planets in the solar system.

The fact that the major-axis of Earth's orbit is not stationary but moves in relation to fixed stars is also unaccounted for here. This affects the length of the precession term, but not the length of the climatic cycles that Earth undergoes.

As explained, the Milankovitch cycles are not the ultimate explanation of climate behavior. But understanding that Earth's movement around the Sun and its own rotation has a decisive impact on Earth's climate in the long term is now one of the cornerstones of our understanding of Earth. ■

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