PROCEEDINGS OF SCIENCE

Milankovitch cycles, eighty years later

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Abstract: Milutin Milankovitch published his influential research "Canon of Insolation and the Ice-age Problem" in Belgrade, Serbia, in 1941. His work is still significant in terms of studying climate changes. In this paper we also consider new scientific knowledge about solar insolation. Periodic solar activities such as sunspots and the magnetic field cycles or grand solar minimum/maximum affect the Earth's atmosphere. These periodic natural factors, together with Milankovitch cycles, are important for regional and for global climate.

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1. Introduction

The Sun provides the energy that drives the Earth’s climate system. This energy is in the form of electromagnetic radiation. Variations in the intensity and spectral frequency of incident solar radiation reaching the Earth cause changes in the global and regional climate. These climate changes are independent of man-made climate change. Milutin Milankovitch proved that climate changes and periodic ice ages on Earth are caused by periodic changes in the movement of the Earth around the Sun and around its axis [1]. He showed that the geometry of the planet's orbit determines the amount of solar energy that reaches the upper layers of the atmosphere. Periodic variations of this geometry change seasonal and spatial distribution of insolation. Because of this, the temperature of the Earth's surface and atmosphere changes, which leads to climate change. This theory is actual in modern science because the problem of climate change, or one can say climate crisis, is one of the main problems of humanity. Solar influence on climate is studied in a series of scientific works (see [2]-[8] and references therein). Emphasis is on the solar variability and global and regional climate responses. These responses are basically divided into millennial, centennial and decadal timescales.

2. Milankovitch cycles, millennial timescales

The first theories about ice ages are presented by geologists. They looked for the cause of the ice ages on Earth - in the interaction between the ocean, land and atmosphere. It turns out that the geologists theories are insufficient to explain the occurrence of the ice ages. Milankovitch looked for the cause of the ice ages in astronomical factors. He succeeded in creating a consistent theory of climate, not only for Earth, but also for other planets of the solar system. The theory consists of two parts-astronomical and physical.

2.1 Astronomical part of the Milankovitch theory

In the astronomical part of the theory, the influence of the movement of the planets on their insolation is explained. This insolation is different in different parts of the year and in different latitudes. The theory is based on the law of gravity, which describes the motion of the planets, and the law of radiation, which describes how solar radiation travels through space and reaches the planets. Milankovitch understood how the geometry of the planet's orbit determines the amount of solar energy that reaches the upper atmosphere. Its long-term quasi-periodic changes alter the seasonal and geographical distribution of incoming solar radiation and this leads to climate change.

The periodicities of the factors that influence the climate are:

1. Periodic tilt changes between the Earth's axis and the direction perpendicular to the plane of its orbit with a periodicity of about 41,000 years;
2. Periodic changes in the eccentricity of the Earth's orbit with a periodicity of about 100,000 years and 413,000 years;
3. Precession in the tilt of the Earth's axis with a periodicity of about 23.000 years.

These long-term quasi-periodic changes are known as secular changes, figure 1.

2.1.1 Periodic changes in the tilt

The tilt changes between the Earth's axis and the direction perpendicular to the plane of its orbit vary between $21^{0}39'$ and $24^{0}36'$. This tilt today is about $23^{0}17'$. Milankovitch determined that when this tilt is greater than the current one, the northern regions receive more solar energy (heat). Snow and ice retreat to higher latitudes and altitudes. When the tilt is lower than the current one, the polar regions receive less solar energy. Snow and ice spread to lower latitudes and altitudes. The differences between summer and winter are reduced and the conditions for the ice age are created. Periodic changes in the tilt are the factors that most affects the climate at higher latitudes. These changes are expressed identically in both hemispheres of the Earth.

2.1.2 Precession in the tilt of the Earth's axis

Precession was first discovered by Hipparchus in 130 BC. Due to the rotation on its axis, the Earth is convex on the Equator. Other planets in the solar system act more strongly on this bulge than on the poles. A coupling of forces is created that forces the Earth's axis to move along a cone (precession) with a period of 25.765 years (Plato's year). Precession is responsible for the movement of the so-called γ point in the retrograde direction along the ecliptic and this determines the duration of the seasons. This factor is especially pronounced in the equatorial region, that is, at lower latitudes.

It can be concluded that in the polar regions, changes in tilt between the Earth's axis and the plane of the ecliptic are dominantly manifested, while in the equatorial region, changes in eccentricity and precession dominate. At mid-latitudes, between 50^0-60^0, all three factors influence equally. In the modern era changes in tilt and eccentricity act in the same way-leading to cooling and precession acts in the opposite direction-leading to warming. The climate will change when all three factors act in the same way.

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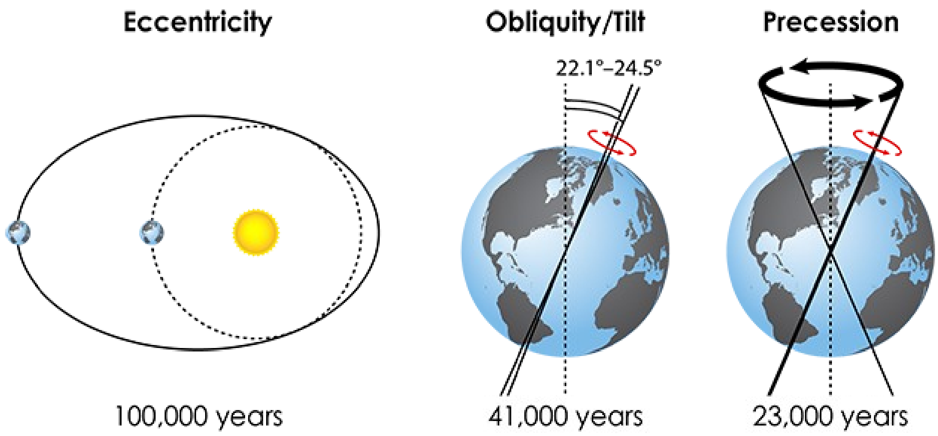

Figure 1. Milankovitch cycles and their periods.

2.2 Physical part of the Milankovitch theory

The physical part of the theory is devoted to the relationship between variable insolation and the temperatures of the land and atmosphere. Milankovitch studied the way in which solar radiation spreads through the atmosphere and reaches the land. The heated land warms the atmospheric layers above it, determining the daily and annual temperatures of the Earth's surface and the lower layers of the atmosphere. Milankovitch laid the foundations of mathematical climatology. He formulated a mathematical relationship between summer insolation and the height of eternal snow and predicted how the surface under the snow would change depending on the variability of summer insolation. He estimated the impact of climatic effects caused by long-term changes on the Earth's albedo. He understood that the prevailing influence on climate change is the insolation of the northern hemisphere because 2/3 of the world's land is located in this hemisphere. Ice ages in both hemispheres are simultaneous because they are caused by the same force - the insolation of the northern hemisphere.

3. Ice ages

The variation of the solar radiation that the Sun sends to the Earth has a completely different meaning if we take into account the long-term variations of the amount of heat received by some place on the Earth's surface and not the entire hemisphere.

The last Ice Age, which ended about 11.000-12.000 years ago, covered half of Europe with ice and turned the Sahara into a green oasis. The ice, whose thickness was about 1.5 km, spread from Scandinavia and Scotland and covered the largest parts of England, Denmark, Germany, Poland and Russia. One huge glacier centered in the Alps covered Switzerland and parts of Austria, Germany, France and Italy with ice. As already mentioned, the first theories about the Ice Age were proposed by geologists. They looked for the causes of the ice ages in the Earth's climate system, that is, in the interaction between the ocean, land, ice and atmosphere. These theories were unsuccessful and it was clear that there were other factors influencing climate dynamics. Milankovitch created a general theory of the climate of the planets (not only the Earth) and a special theory about the influence of the movement of the Earth on its insolation and climate. His work made a huge contribution to solving the problem of the Ice Age.

In the period between 1921-1924, Milankovitch calculated the amount of insolation for these latitudes: 5^0, 15^0, 25^0, 35^0, 45^0, 55^0, 65^0 and 75^0 in both hemispheres. He graphically presented these results for the period of the last 600.000 years and obtained the famous curves -curves of insolation. The results were published in Milankovitch most important book -*Canon of Insolation and the Ice Age Problem* [1]. He concluded that insolation at high latitudes, 75^0 in the northern and southern hemispheres, is almost the same; in tropical regions at 15^0 latitude in both hemispheres the flux of insolation is opposite while in middle latitudes this flux is neither the same nor opposite. This is the result of the dominant influence of periodic changes in inclination (tilt) at high latitudes and the dominant influence of periodic changes in eccentricity and precession at low latitudes.

Incoming solar radiation represented by Milankovitch curves found application in geology enabling the creation of Ice Age chronology. The first to see the potential of Milankovitch's work were Köppen and Wegener. They published insolation values for 55^0, 60^0 and 65^0 N [9]. Köppen claimed : "the diminution of heat during the summer half-year is the decisive factor in glaciation". With Köppen approval, Milankovitch preferred not to reproduce anymore the numerical values of insolation themselves, but rather to transform them in fictitious latitudes, called the 65^0N equivalent latitudes; this was first published in his *Mathematische Klimalehre* [10]. These latitudes are actually present-day Northern Hemisphere latitudes that receive the same radiation during the summer half-year as 65^0N latitude in the past. A fictitious motion of these latitudes to the south corresponds therefore to an increase of the summer irradiation. Cold periods, nine of them, calculated according to Milankovitch scheme, can be classified into four groups. These are the four glacial periods of the Penck-Bruckner scheme (Günz, Mindel, Riss, Würm) recognized by Köppen in the Milankovitch 65°N equivalent latitude, figure 2. The reflective power of the polar caps, in addition to the long-term variations of insolation [11], according to Milankovitch is "absolutely sufficient to explain the full extent of even the greatest climatic events of the Quaternary and to clearly show their causes". With his contemporary colleagues, Penck, Brückner, Köppen and Wegener he could show that his mathematical climate fits well the geological reconstruction of climate available at these times (for details see [12]).

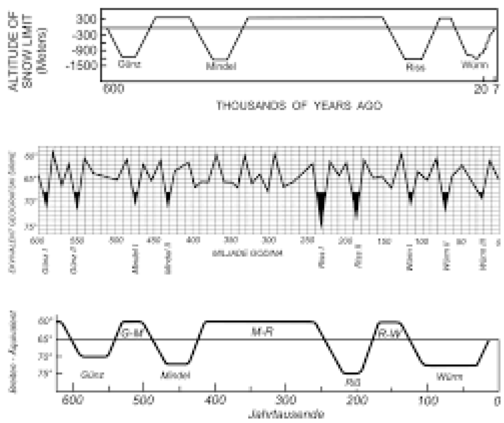

Figure 2. Inclusion of Milankovitch data into Köppen's and Wegener's considerations. Uppermost panel: Penck and Brückner's curve showing the climate during the Pleistocene period (published 1909). Middle panel: Milankovitch's radiation curve for latitude 65°N forwarded to Köppen in 1924. Lower panel: Sequence of Late Quaternary Glacials and Interglacials (after Penck & Brückner, 1909) adapted to their timing deduced from Milankovitch's radiation curve by drawing a horizontal line at latitude 65°N (cited from Berger, [13]). These images agree surprisingly well even though they were obtained in two completely different ways - geological research and astronomical calculation.

4. Modern insights into the Milankovitch cycles and their impact on climate change

Astronomical theory of the ice ages has the evidences in the geology, biology and other researchers. The CLIMAP project (Climate, Mapping, Analysis and Prediction) definitely confirmed this theory. This project was established in the 1970s to study the global climate [14]- [16]. The next project was COHMAP (Cooperative Holocene Mapping Project) in 1980s and 1990s [17].

Paleoclimate is currently being researched in many laboratories around the world. The Alfred Wegener Institute Helmholtz Center for Polar and Marine Research in Bremerhaven, Germany, researches past, present and future climate changes from a polar perspective. Based on traces enshrined in ice cores and sediment cores, reconstruction of past climates is now possible in much greater detail due to the development of new proxies. It enables not only analysis of paleotemperatures, but also of ice coverage, carbon dioxide and methane in the atmosphere, wind speed and many other variables of past climates [18]. In contrast to Köppen's and Wegener's times, however, nowadays not only the natural dynamics are shaping the climate, but also anthropogenic impacts have to be considered complicating the already complex matter of climate processes.

4.1 Cenntenial timescales

On these timescales, long-term changes in the Earth's orbit may be disregarded. Quasi-bicentennial solar cycles are the primary cycles that govern variations in the 11-year subsidiary cycles in TSI (total solar irradiation) and solar activity [19]. In the growth phase of the quasi-bicentennial solar cycle, the Earth receives more solar energy than is emitted by radiation into space, and its average annual energy balance is positive (E > 0), and vice versa in the recession phase of the quasi-bicentennial cycle it is then negative (E < 0). As a result, the average annual energy balance of the Earth oscillates around the quasi-bicentennial equilibrium state. Another interesting approach is made by Valentina Zharkova by introducing magnetohydrodynamic (MHD) waves in the definition of solar activity [20], [21]. This approach revealed a presence of grand solar cycles with duration of 350-400 years, figure 3. These grand cycles are always separated by grand solar minima of Maunder minimum type, which regularly occurred in the past forming well known Maunder, Wolf, Oort, Homeric and other grand minima.

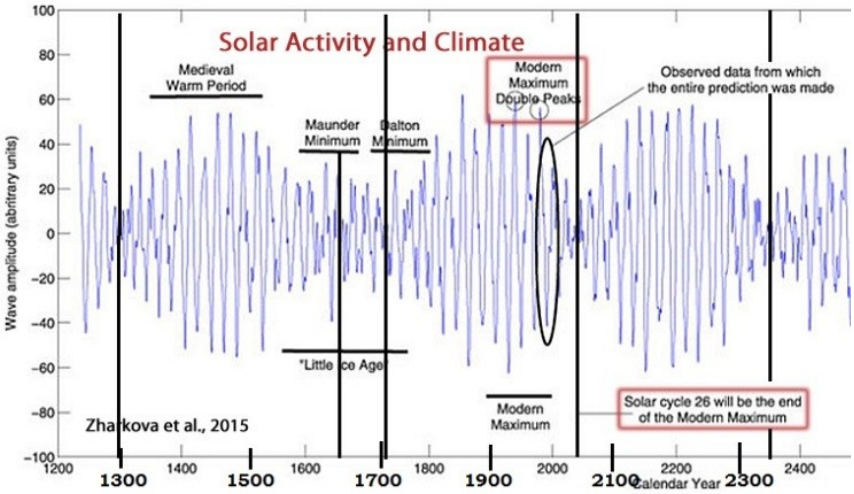

Figure 3. Reconstruction of solar activity for the period 1200-2400 years by superposition of MHD waves in the interior of the Sun.

According to this study the contemporary grand solar minimum started in 2020 year and will last until 2053. This global cooling during the coming grand solar minimum may offset in three decades any sign of global warming.

4.2 Decadal timescales

The most famous features on the Sun in decadal time intervals are sunspots. Sunspots are dark areas that appear on the solar photosphere in cycles lasting between 9 and 13 years. These cycles are commonly known as 11-year solar cycles. The Sun's electromagnetic radiation varies within these solar cycles so that the Sun emits more radiation at sunspot maximum, i.e. when it is most covered by dark sunspots. The very small number of sunspots (only a few) in the years 1645-1715, the period known as the Maunder Minimum, coincides with the so-called Little Ice Age in Europe and North America. Today, the influence of 11-year solar cycles is studied within two mechanisms: bottom-up and top-down [22], [23]. Decadal solar variations appear to have a greater influence on regional than on global climate responses [24].

5. Conclusions

The problem of climate change is a multidisciplinary problem that is very current in today's society. Eighty years ago, Milutin Milankovitch managed to integrate astronomy, mathematics and geophysics and create a wonderful and timeless theory. Since no hypotheses were introduced in the calculations, Milankovitch decided to call his results the *Canon of insolation*. The book was printed on April 6th, 1941, when Belgrade was bombed at the beginning of the Second World War. Fortunately, the book was not destroyed.
Just as Köppen in 1922 had an inkling that Milankovitch theory could be an invaluable tool for researching ancient climates, so modern science realizes that without it, one cannot study or predict the future climate, especially the synergistic action of natural and anthropogenic factors on the Earth's climate system. New insights about millennial, centennial and decadal time frames of solar activity will lead to more detailed knowledge necessary for the prosperity of the human race.

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