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A hundred years of Milutin Milanković's climate change theory – geological implications

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Key words:

*cyclostratigraphy,
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Geologic Time Scale,
climate changes, continental drift.*

Кључне речи:

*циклостратиграфија,
астрономска временска скала,
геолошка временска скала,
климатске промене,
континентални дрифт.*

Abstract. Milanković's cycles theory published hundred years ago is the most important theory in climate science and had great influence on Earth disciplines. Nevertheless, his work waited for more than fifty years for confirmation. It could be said that Milanković's work had most influence in creation of Astronomic Time Scale, supporting of continental drift hypothesis and palaeoclimatology implications.

Positive results of the implementation of the astronomic time scale to the Neogene stratigraphy initiated the application of this method within the Mesozoic, and lately also to the Paleozoic sediments. Milanković's manuscript of astronomical forcing of climate changes led to fruitful cooperation with Alfred Wegener who was searching for additional arguments to validate his continental drift hypothesis. The factors that cause climate changes enable insight to the geological past, but also the possibility to model the climate conditions which await us in the future. Climate change prediction allowed people, as only being aware of its influence, to act preventively and take all measurements needed to reduce greenhouse gasses emission.

Апстракт. Миланковићева теорија циклуса објављена пре сто година је најважнија теорија у наукама које проучавају климу и имала је велики утицај на дисциплине које се баве Земљом. Ипак, његов рад је чекао више од педесет година да би добио потврду. Може се рећи да Миланковићев рад највећи утицај на геологију има у изради астрономске временске скале, подршци хипотези континенталног дрифта и палеоклиматологији. Добри резултати примене астрономске временске скале на неогене седименте иницирали су примену ове методе у мезозојским и у последње време палеозојским седиментима. Миланковићев манускрипт о астрономским утицајима на климатске промене довео је до успешне сарадње са Алфредом Вегенером који је тражио додатне аргументе који би подржали његову хипотезу континенталног дрифта. Разлози који доводе до климатских промена омогућили су поглед у геолошку прошлост, али и моделовање климатских услова који нас чекају у будућности. Прављење прогнозних модела климатских промена омогућава људима, као јединим бићима свесним свог утицаја на њих, да делују превентивно и предузму све мере у циљу смањења емисије гасова стаклене баште.

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Introduction

In the year 1920, Serbian scientist Milutin Milanković published his crucial work - "Mathematical Theory of Heat Phenomena Produced by Solar Radiation" (Fig. 1) and enabled us to understand the mechanisms and causes of climate changes. This is definitely one of the most important scientific theories in the climate science. The influence of his work is not just related to climatology but also to applied mathematics, physics, astronomy, and geo-

It could be said that Milanković's contribution to Earth science could be placed in the base of the three pillars: high resolution astronomic time scale, continental drift and both climate changes of the distant past and their future forecasts. Also, it is remarkable that even the fact that he was affected by two World Wars and spent time in prisoner-of-war camps did not lose his determination to work on some of the most intriguing scientific problems. Because of the huge interest in long-term climate projection and demand for high-resolution time scale it

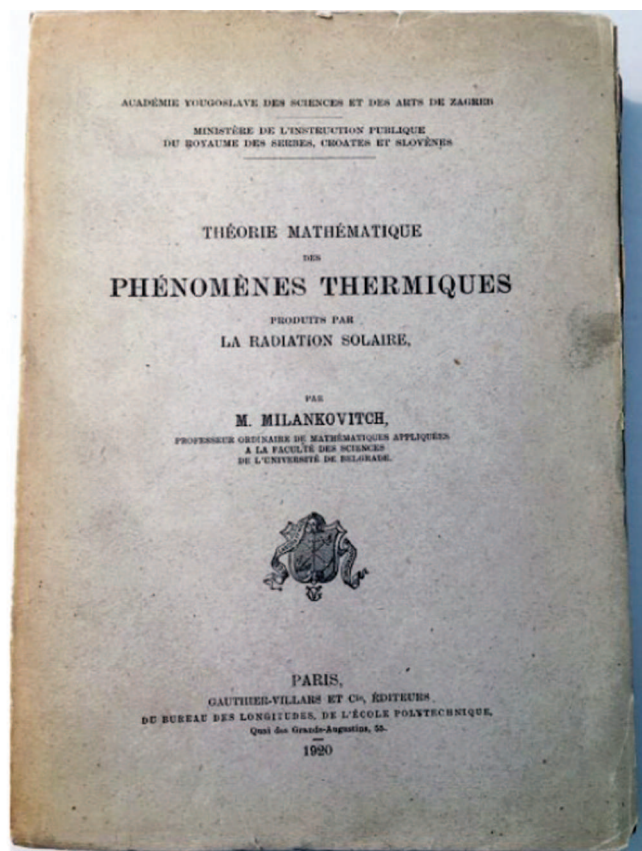


Fig. 1. Milanković's bust at the Faculty of Mining and Geology, University of Belgrade (left) and original front page of his famous theory published by Académie Yougoslave des Sciences et des Arts de Zagreb (right) (MILANKOVIĆ, 1920).

logy. At first, geologists have not recognized how important Milanković's work will be for their future research and its final confirmation will come more than 50 years afterwards (HAYS et al., 1976). During his lifetime, Milanković cherished his friendship with many famous geologists like father of continental drift Alfred Wegener and Serbian Academic Petar Stevanović among others.

is correct to say that Milanković's work is still far for full implementation.

Short biography

Milutin Milanković was born on 28th May 1879 in Dalj (Austro-Hungarian Empire, actually Croatia).

Besides his twin sister he had three brothers and two other sisters. His father Milan was very wealthy farmer but unfortunately passed away when he was eight years old. Also, his brothers died from tuberculosis at young age and besides his mother Jelisaaveta and grandmother, his uncle Vasilije Maučević took care of him and sisters. In 1889 he left to his uncle Paja Maučević to Osijek where he went to Gymnasium and very soon became the best student even though before he was educated solely by private teachers and governess. Since there was not electrotechnics at Vienna Technological Institute (actually Technische Universität Wien) he went to civil engineering and graduated in 1902. He continued his Vienna studies and at age of 25 (on December 12th, 1904) gained a PhD and become the first Serbian Doctor of Technical Science. As a construction engineer, he was one of the pioneers of reinforce concrete application, had six patents (eight in total), and get a glory as well-paid innovator.

In 1909 he received an offer from the University of Belgrade to work as an Associate Professor at the Department of Applied Mathematics. He moved to Kingdom of Serbia in 1910 and became its citizen, even though his salary was ten times lower than in Vienna. To gain additional money, he took part-time jobs working on statical calculations for construction projects.

The Great War caught him on honeymoon in his hometown and he was imprisoned in a war camp at Neusiedl am See (Nežider), Austria. His wife Hristina travelled to Vienna and intervened with his professor Emanuel Czuber to help Milutin's desperate situation. After six months at the prisoner-of-war camp he was transferred to Budapest where he spent the rest of the WWI under police surveillance working in the Library of Hungarian Academy of Science and Hungarian Meteorological Service. Even being in house arrest he continued working on research and finished new mathematical theory of astronomical forcing of climate changes in 1917. Nevertheless, he had to wait for its publication until 1920. The same year he was promoted as a member of Serbian Royal Academy.

In 1923 he proposed the revision of the Julian calendar which was adopted by some Orthodox churches. The compiled work about understanding

of climate history of planet Earth and astronomical forcing of climate changes was published in his most famous piece "Canon of Insolation and the Ice-age Problem" (MILANKOVIĆ, 1941).

During the WWII he became isolated from public life and spent time writing autobiography "Uspomene, doživljaji i saznanja" ("Memories, experiences and cognition") (MILANKOVIĆ, 1952). After the war, the most cited Serbian scientist ever became a Vice-president of Serbian Academy of Science in three mandates (1948–1958) and acted as a Head of Astronomical Observatory in Belgrade in period 1948–1951.

There are many landmarks expressing acknowledgment of Milanković's work. Acknowledging Milanković's contribution, NASA listed him as one of fifteen most important Earth scientist ever (GRAHAM, 2000). One crater on Mars and one crater on the opposite side of Moon were named after him as well as a lot of prestigious scientific rewards, honors and institutions (including Geological and Hydrometeorological High School in Belgrade) and numerous monuments, busts etc. (Fig. 1).

Milutin Milanković passed away in Belgrade on December 12th, 1958.

Cyclostratigraphy and Astronomic Time Scale (ATS)

A precise geological time scale is essential for understanding and interpretation of the geological processes on planet Earth. To reach most accurate high-resolution time frame of the Earth's past, scientist turned to astronomic cycles from which most significant are Milanković's ones (precession, obliquity, and eccentricity) with periods ranging from 20 to 400-kyr (Fig. 2). Those phenomena initiated the changes in the climate, ocean water circulation, sedimentation rates and life conditions of the biosphere which could be potentially preserved within the sedimentary record. Except them, there are also longer period cycles so-called "grand cycles" of 400 kyr, and 1.25, 2.35 and 4.6 my (OLSEN, 2001). The effects of these longer period cycles are only potentially noticeable in climate records of several to tens of millions of years.

The Milanković's cycles are the basis of cyclostratigraphy, one of the youngest stratigraphic

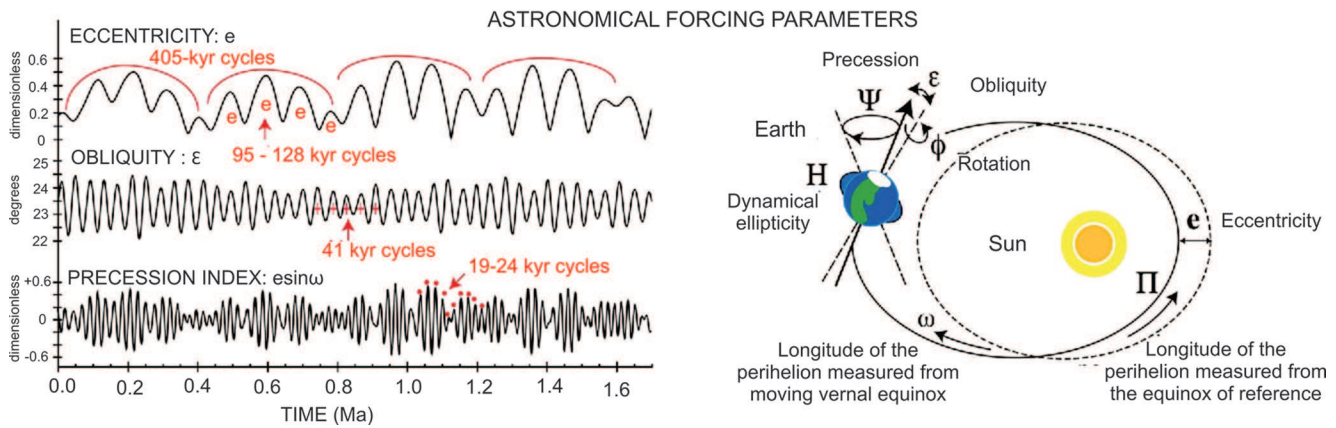


Fig. 2. Parameters affecting Earth-Sun position(right,) and oscillations shown for past 1.6 million years (left, LASKAR et al., 2004) (modified, HINNOV & OGG, 2007). Main periodicities are indicated in red.

disciplines which deals with the determination, characterization, correlation, and interpretation of cyclic changes in the stratigraphic record by using astronomical parameters of known duration to determine the time factor of the sedimentary record (STRASSER et al., 2006). The main goal of cyclostratigraphy is to increase the accuracy and resolution of the stratigraphic timeframe. The evidence of climate change that corresponds to solar cycles could be found in sedimentary rocks (Fig. 3) by interpretation of strata according to their glacial or interglacial characteristics. Sedimentation rates spatially and

temporary varies and depend on palaeoecological and palaeogeographic conditions. Generally, well-rounded and fine-grained sediments reflect calm and slow sedimentation, while angular coarse-grained sediments are mostly related to short palaeotransport and fast sedimentation. We have to be careful during the sampling since the potential pitfalls and misinterpretation could be caused by hiatuses, bioturbation, reworked sediments, and erosion.

The astronomical tuning method enhances traditional geological dating methods and over the last decade has been successfully applied to a continuous high-resolution geological time scale (GTS) correlation (SCHWARZACHER, 1993; SHACKLETON et al., 1999). On the GTS 2012 (GRADSTEIN et al., 2012) most of the Cenozoic era was directly calibrated with the ATS (Fig. 4). The International Commission on Stratigraphy encouraged with good results of Neogene ATS decided to complete a continuous ATS for the past 250 Ma, especially because continuous ATS can restore loss in precision and accuracy between widely spaced horizons that can't be solved by high-precision radioisotope geochronology (HINNOV & OGG, 2007).

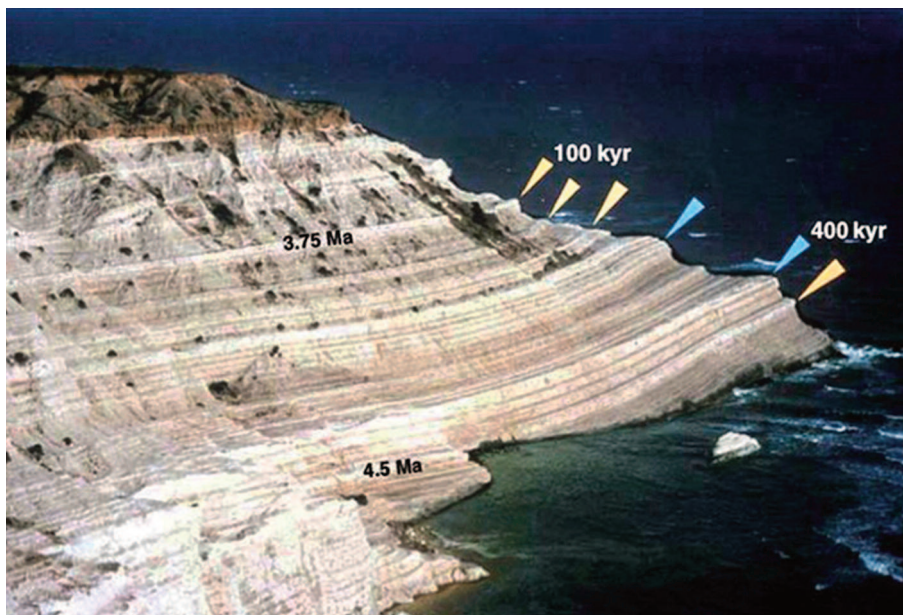


Fig. 3. Example of Milanković's cycles at geological section in Punta di Maiata, Sicily (HILGEN et al., 2006).

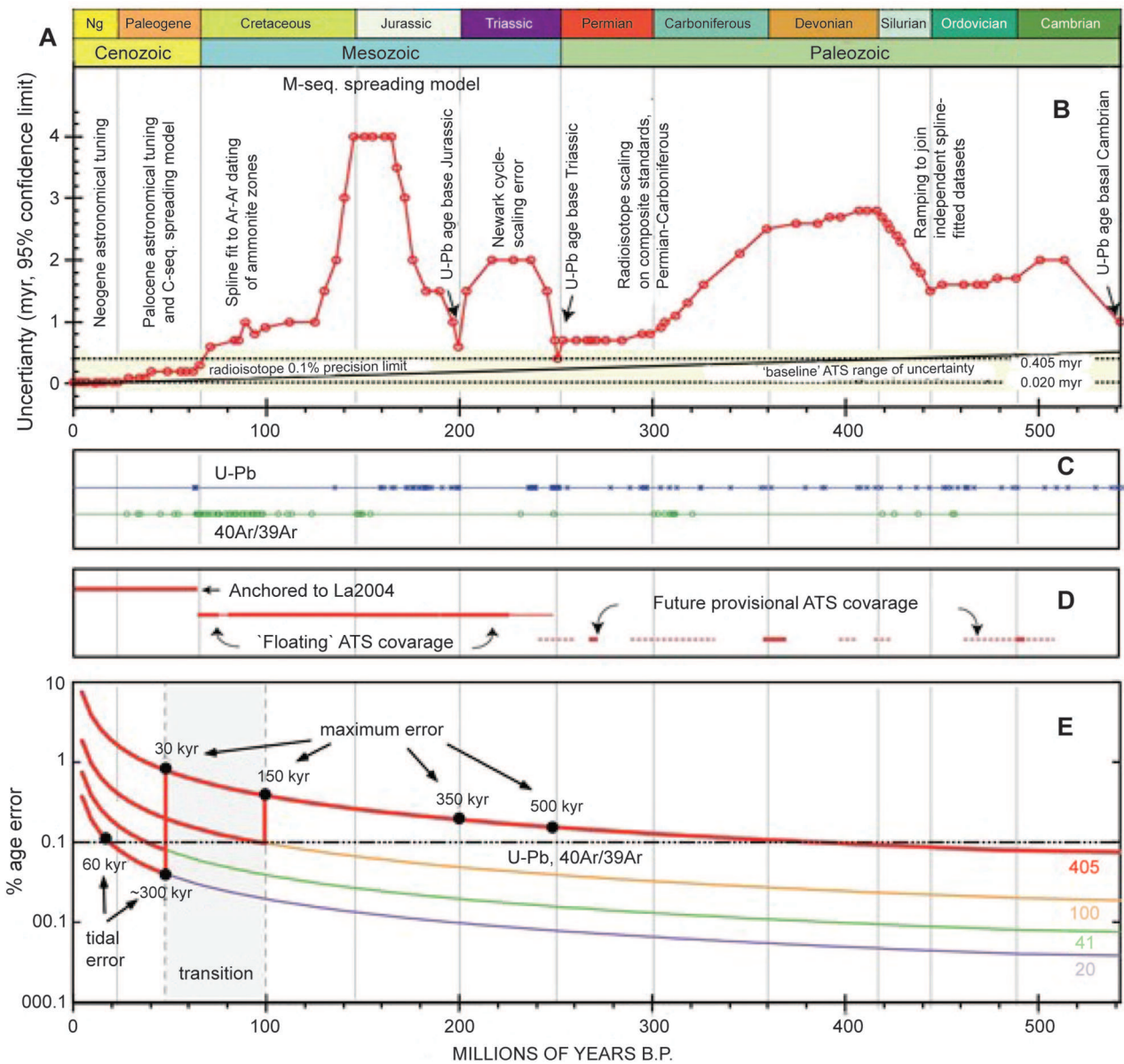


Fig. 4. Uncertainty in the Phanerozoic International GTS 2004 (GRADSTEIN et al., 2004). **A**, Standard GTS division, modified; **B**, Estimated uncertainty (95% level of confidence); **C**, Distribution of U-Pb and 40Ar/39Ar; **D**, distribution of astronomically forced cyclostratigraphy during Phanerozoic. Thick solid lines indicate cyclostratigraphy contributing to the absolute ATS, thin solid lines indicate gaps; dashed lines indicate reported cyclostratigraphy with potential to yield ATS information. **E**, age error percentage (from HINNOV & OGG, 2007).

As an example, the recent research on the Triassic Chinle Formation in Petrified Forest National Park in Arizona confirms the existence of a foreseen 405,000-year Milanković's cycle influenced by the movement of the planets Jupiter and Venus. The core samples from the Chinle Formation were dated and correlated to Newark Basin Triassic rocks to determine climate cycles age and timing logged in the rocks and represent the material geologic evidence of 405 kyr Milanković's cycle (CALLIER, 2018).

ATS based on Milanković's forced stratigraphy, calibrated with palaeoclimatic forcing is well defined for the Cenozoic and Mesozoic. However, for the Paleozoic era, astronomical forcing has not been extensively researched due to the lack of precise geochronology or astronomical modelling. A recent study by Wu et al. (2013) examined Milanković's cycles in the Lower Permian strata in southern China which were time-calibrated with high-precision U-Th dating (Fig. 5).

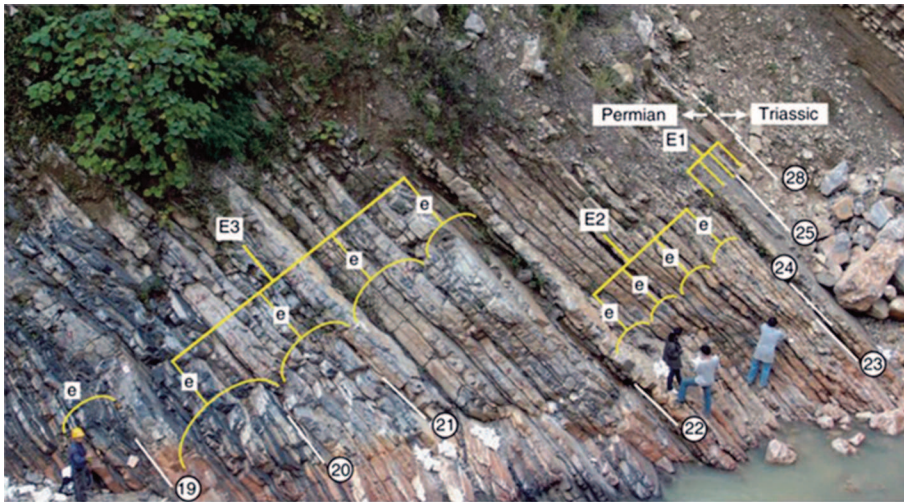


Fig. 5. The lower Permian ATS calibration of Upper Changhsingian Dalong Formation at Shangsi section. Thin precession-scale beds of 100-kyr eccentricity cycles (*e*), 100-kyr cycles are bundled into 405-kyr eccentricity cycles (*E*) (WU et al., 2013).

In this way, empirical knowledge about astronomical parameters is related to events from 250 million years ago. The observed cycles support the existence of a day that lasted 22 hours (WU et al., 2013). This is the first significant piece of evidence in defining the Paleozoic ATS, which is based on absolute time and thus connects the Paleozoic-Mesozoic transition.

Continental drift

Even though Milanković and Wegener were not Earth scientists, they created two major scientific revolutions in geology which could be compared to theory of evolution or theory of relativity (PETROVIĆ & MARKOVIĆ 2010). Milanković's work was noticed by meteorologist and astronomer interested in geophysics, Alfred Wegener, and climatologist Vladimir Petrovič Köppen. Köppen impressed by calculation of secular thermal change, invited Milanković to consider the periods of 130 ky and 600 ky to his calculations. During his discussions with Wegener, Milanković got interested in the Earth's interior and its pole movements. Both were intrigued with enormous reserves of bituminous coal at Svalbard Islands in Arctic Ocean since the current high latitude is not favorable for its deposition. Three scientists agreed that occurrence of cold summers was crucial to the

proposed model. Milanković worked on Solar insolation changes for past 650 kyr for more than 100 days which later was used in the study "The Climates of the Geological past" (KÖPPEN & WEGENER, 1924). The mutual work of Köppen, Wegener and Milanković result in precise Quaternary glacials and interglacials timescale. Milanković's regularly changing orbital parameters added necessary periodicity to Köppen's climate zonation and supported Wegener continental drift hypothesis.

Sadly, their friendship and collaboration suddenly ended when Wegener tragically died during his fourth Greenland expedition from hypothermia in 1930. After that Milanković was even more motivated to find evidence which will support Wegener's continental drift idea and expressed gratitude to his work in 1934 in a paper titled "O pomeranju Zemljinih polova, Uspomena na Alfreda Vegenera" ("On the wandering of the Earth's poles – a remembrance of Alfred Wegener") (MILANKOVIĆ, 1934; Fig. 6)

Unfortunately, both great scientists shared the same cruel destiny since their work got truly acknowledged long after their deaths. Milanković's theory awaited confirmation until HAYS et al. (1976) studied about deep-sea sediment cores from the southern Indian Ocean during CLIMAP project. Hays and the coauthors were finally able to correlate climate fingerprints containing the Milanković's cycles after which the National Research Council of the U.S. National Academy of Sciences has embraced the model of Milanković's Cycles.

Earth climate changes - past and future

Milanković's cycles provided an understanding of the last ice age and are used for explanation of climate changes of the geological past. The planet Earth had several episodes of glaciations from

О ПОМЕРАЊУ ЗЕМЉИНИХ ПОЛОВА.

Успомена на Алфреда Вегенера.

Од М. Миланковића,
професора Универзитета, Београд.

Смрт Алфреда Вегенера, генијалног немачког геофизичара и неустрашивог научног путника у поларне крајеве, била је тежак ударца за науку. И ја сам лично осетио сву тежину тога удараца, јер ме је са Вегенером везивало лично пријатељство којег нмам да захвалим за многи потстрек у мом научној раду. То важи нарочито за моја истраживања о померању Земљиних полова. Историјат тих истраживања, о којем овде укратко извештавам, неодољан је од успомена на Вегенера. Зато је овај мој чланак добио горњи двоструки наслов.

Упознао сам се још пре рата, из даљине, преко њених научних радова које смо један другом слали. Те наше везе постајале су временом све јаче. Вегенер је постао зет Владимира Келена, славног климатолога, а са овим сам, после публикације мога дела о математичкој теорији климе, отпочео живу научну преписку које до данас није мала. Келен је, иако му је онда било 75 година, са великим интересовањем проучио то моје дело, и увидео да мој научни рад допуњава област истраживања о клими Земљине прошлости о којој су он и Вегенер сиремали засебно дело. Тако сам, септембра месеца 1922. добио од Келена писмо у којем ме, у своје и Вегенерово име, позива на сарадњу на том њиховом делу. Почетком лета 1924. године извршио сам коректуре ових табака њихове књиге који су садржавали мој текст, а у јесен те године успознао сам се лично са Вегенером.

Било је то у Инсбруку септембра месеца. Ова лепа алијска варош, снабдеvena свим комфором за путнике, показала се тада сувише мала да прими огромни број странаца којих је већину привукао конгрес немачких природњака и лекара. И ја сам дошао да присуствујем седницама за тога научног састанка, да се лично упознам са Вегенером и саслушам реферат о његовом и Келеновом новом делу, који је стајао на дневном реду седница конгресних. Чим сам стигао у Инсбрук, дао сам се у потеру за Вегенером. Али, како га лично нисам познавао, није била лака ствар пронаћи га у оном мравњачу научника, који је испунио све сале



Alfred Wegener

1880—1930

Fig. 6. Front page from paper in which Milanković expressed gratitude to his friend Alfred Wegener, father of continental drift hypothesis (MILANKOVIĆ, 1934).

which the five most important ones are: the Huronian (2.4–2.1 billion years), the Cryogenian (850–635 million years), the Andean-Saharan (460–430 million years), the Karoo (360–260 million years) and the Oligocene-recent (Fig. 7). In the last million years, a dozen glaciations have occurred, while the last glacial period reached its peak 18.000 years ago, before the beginning of the Holocene interglacial.

The planet Earth has undergone through warm (greenhouse) and cold weather conditions (icehouse) several times during its history (Fig. 8).

The greenhouse period, in which Earth has spent 85% of its time, is characterized by absence of continental glaciers, and high levels of carbon dioxide and other greenhouse gases (PRICE et al., 1998). The global sedimentary record contains data on a high carbon dioxide levels and other greenhouse gases in the geological past (e.g. during Ordovician Period the amount of CO₂ was 10–18 times higher than today) (POUSSART et al., 1999). The plate tectonics regimes were more intensive during the greenhouse

periods when volcanic activity and increased carbon dioxide release caused warming of the Earth's atmosphere.

During the Earth's icehouse periods there are no less than two ice sheets on the planet's polar regions, the Arctic and the Antarctic. These covers increase and decrease in volume during a shorter intervals identified as glacial periods (including the formation of additional ice sheets besides the two at the poles) and interglacial episodes (exclusive of additional ice sheets). During the icehouse period, the concentrations of the greenhouse gases in atmosphere are relatively low and temperature shows a global decline. Decreased volcanic activity and continental drift which affected the opening and closure of the ocean passages were probably the main cause of icehouse periods. Additionally, tectonic activity drives mountain building processes (e.g., Himalayas, approximately 50 million years ago) (DEWEY et al., 1989) while the formation of new soil acting as a carbon dioxide absorber significantly af-

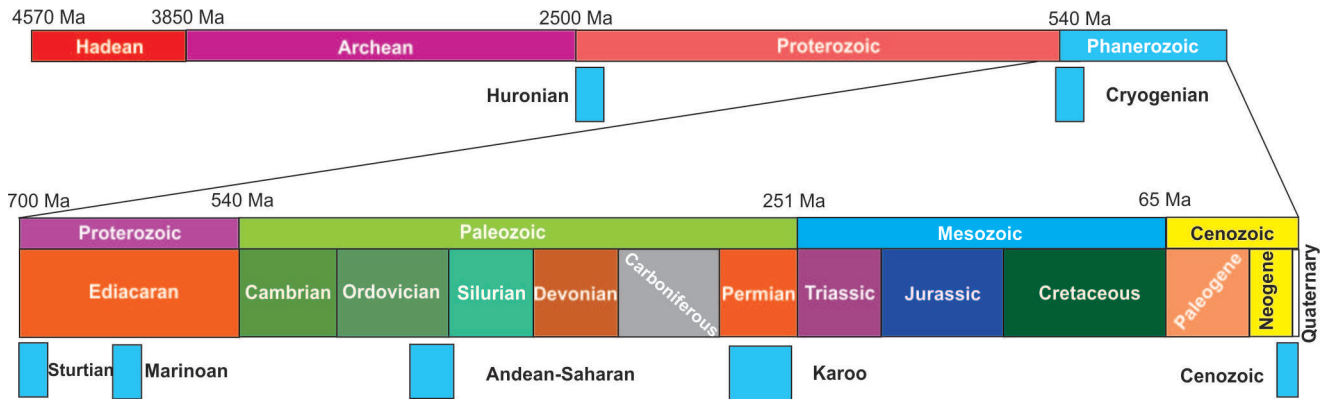


Fig. 7. Timeline with major glaciations during Earth's history (EARLE, 2015).

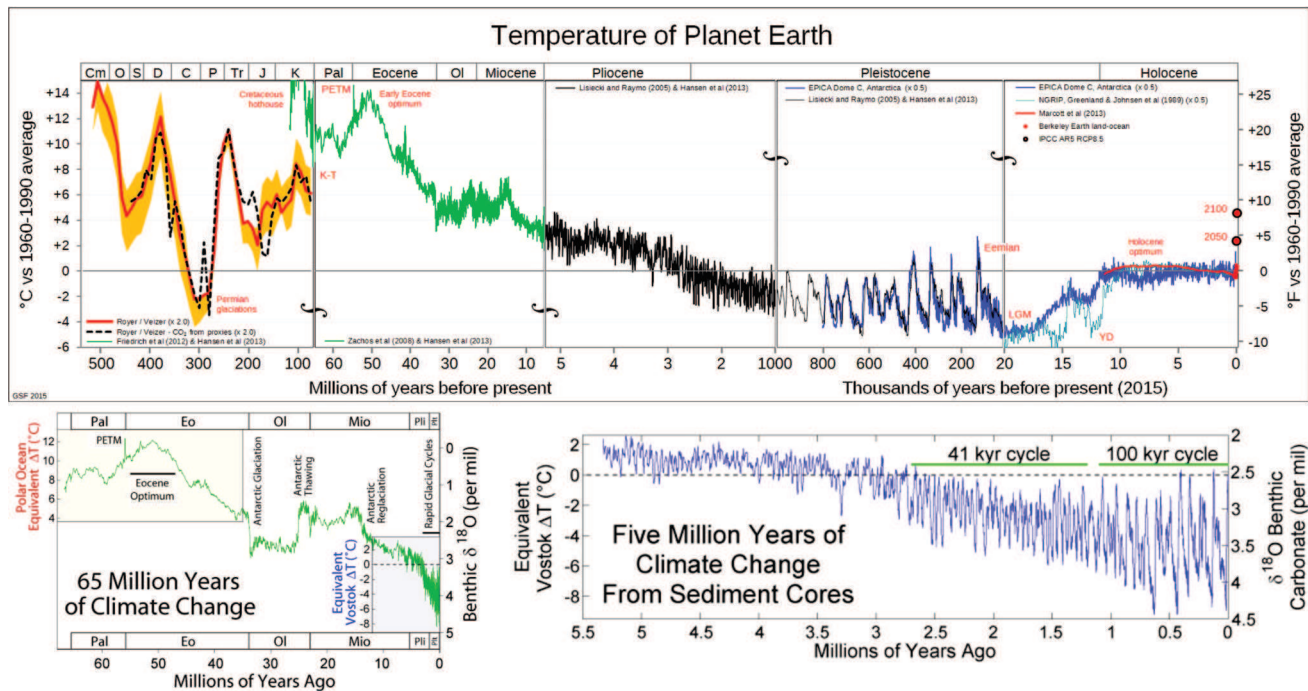


Fig. 8. Assumed temperature during the Phanerozoic (FERGUS, 2015), the Cenozoic (bottom left, courtesy by ROBERT A. ROHDE, Global Warming Art) and in the last 5.5 million years (bottom right, courtesy by ROBERT A. ROHDE, Global Warming Art).

affects the amount of greenhouse gases in the atmosphere.

The main consequences of the interactions of the atmosphere and the geosphere are best observed in the relatively recent events while during the geological “deep” time these relations become blurry. As an example, from the end of the Paleocene (55.8 Ma ago) to current glaciation, the global average temperature dropped by about 14°C (Fig. 9). The Antarctic Circumpolar Current (A.C.C.) prevents warm

water from the rest of Earth’s oceans to reach Antarctica (Fig. 9). This seems to have played a key role in the formation of the icehouse due to the upwelling of cold water from the deeper parts of the water column that aided the formation of ice sheets.

The Late Cenozoic Ice Age that began 33.9 million years ago was probably caused by opening of the Tasmanian Passage (separating Australia and Antarctica; EXON et al., 2000) and Drake Passage (between South America and Antarctica; SCHER&MARTIN,

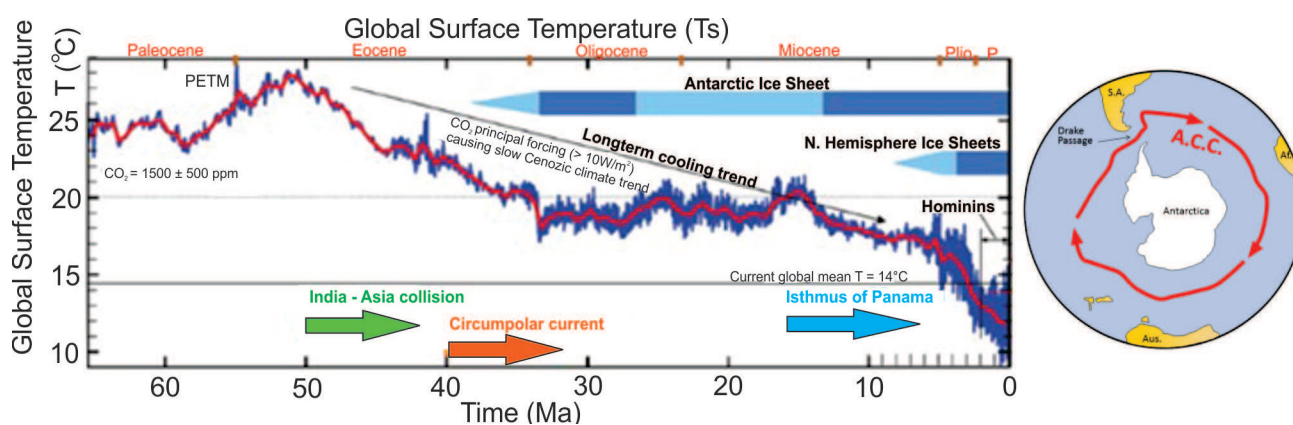


Fig. 9. The global temperature trend during the Cenozoic (65 Ma). There is a significant temperature drop (about 14°C) from the end of the Paleocene toward the Pleistocene Glaciation. (PETM - Paleocene-Eocene thermal maximum) (ROUTLEDGE, 2013, <http://www.alpineanalytics.com/Climate/DeepTime.html>, left). The Antarctic Circumpolar Current (red arrows) prevents warm water from the rest of Earth's oceans from getting close to Antarctica (right, EARLE, 2015).

2006). The Isthmus of Panama and closing of the Indonesian seaway about 3–4 million years ago may be the main cause of the current icehouse period (CANE & MOLNAR, 2001).

Besides enabling us to return to the past, Milanković's work also allows insight into the future. His work provides a basis for climate change prediction. The Paleocene-Eocene temperature maximum (PETM) is of special importance for climatologists since it represents the excellent analogue for climate prediction modelling. The PETM is marked by a short (100,000 years) clear drop in value associated with sudden warming and was marked by the highest temperature during the Cenozoic. Even though, its causes are not clear, some scientists suggest that main factor for its occurrence was the sudden release of methane hydrate from oceanic sediments caused by massive volcanic eruptions.

Recent study by GINGERICH (2019) compared the rate of greenhouse gas accumulation in the PETM to modern climate change today (Fig. 10) and find out that anthropogenic carbon emissions at the present are occurring 9–10 times faster than during the PETM period.

It is calculated that by the year 2300 the concentration of carbon dioxide in the atmosphere will exceed 2000 ppmv (CALDEIRA & WICKETT, 2003) due to emissions from the consumption of fossil fuels. The carbon emission into the atmosphere and oceans

corresponds to one which occurred on the Paleocene-Eocene boundary and led to intense global warming. The increase of carbon dioxide emissions into the atmosphere, which in 2011 exceeded 390 ppmv (TANS & KEELING, 2011), has not been recorded in geological history. At the present rate of greenhouse gas emissions, it is calculated that we could expect to see PETM-scale climatic changes approximately by year 2160 (GINGERICH, 2019).

The climate and biogeochemical response to such a rapid and large increase in carbon dioxide in the atmosphere will be very harsh, especially on continents that are settled at higher latitudes. Additionally, the effect of it will be noticeable in the oceans, where the increase of acidity and dissolved calcite will affect marine organisms with carbonate shells (THOMAS, 1998, 2003, 2007). This increase in vertical gradients can lead to a decrease of the Oxygen Minimum Zone (OMZ) and the formation of almost anoxic conditions such as those in the Black Sea or the Gulf of Mexico (JOYCE, 2000). The analyses conducted on foraminifera confirmed the similar situation during PETM (CHUN et al., 2010; NICOLO et al., 2010).

In recent years, climate changes have been a heated debate both, in the media and scientific circles. People have become aware of its influence on the increased emission of carbon dioxide and temperature rise. As a result, many oil and other large manufacturing companies came under the public at-

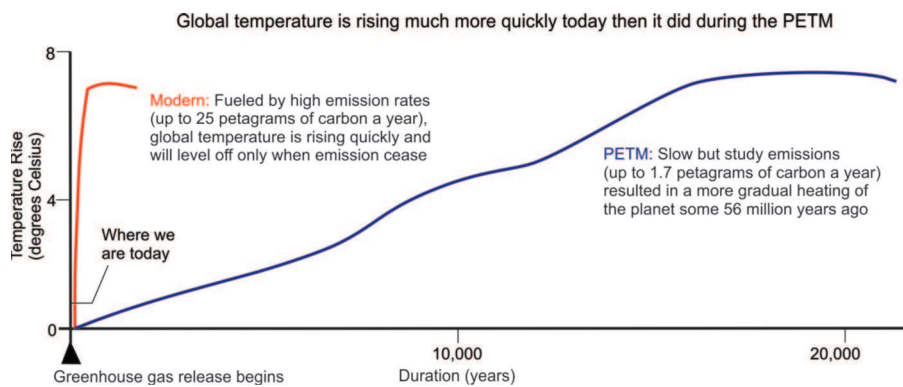


Fig. 10. The temperature change caused by greenhouse gas accumulation during PETM and technogenic activities (SINCLAIR, 2011).

tack and were forced to adapt to the new business conditions (SKJÆRSETH & SKODVIN, 2001; NASIRITOUSI, 2017; RADIVOJEVIĆ, 2020).

Conclusions

Probably the most influential climatic study ever, Milanković's "Mathematical Theory of Heat Phenomena Produced by Solar Radiation" was published hundred years ago. His theory affected geology and its different branches like stratigraphy, palaeoclimatology, tectonics etc.

Recently a lot of scientific studies are focused on Astronomic Time Scale calibration for the Paleozoic Era after getting good and promising results for the Cenozoic and Mesozoic sediments. Milanković's work supported one of the most important theories in geoscience ever (continental drift) and contributed to understanding of climate in the geological past. His work on climate changes represents the core for climate modeling which allows prediction of possible scenarios awaiting us. Having this in mind, it is possible to invest more financial and intellectual resources to reduce human influence on greenhouse gas emission.

Besides being a brilliant scientist Milanković was a patriot strongly attached to Serbia, where he decided to settle down despite much better financial conditions he had in Austria. His determination and love for science was so strong that he managed to achieve important discoveries during challenging

times, in the course of two World Wars, and he represents a great role model for young scientists.

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Резиме

Стогодишњица теорије климатских промена Милутина Миланковића и њен утицај на геологију

Пре тачно сто година Милутин Миланковић је објавио једно од својих најутицајних дела под називом „Математичка теорија топлотних појава изазваних сунчевим зрачењем“. Иако дуго оспоравана, његова теорија о климатским променама је поред климатологије имала изузетно велики утицај и на друге природне науке укључујући геологију.

Миланковић је рођен 1879. године у Даљу, тадашњој Аустроугарској монархији, а високо

образовање и докторат стекао је у Бечу. Пет година након доктората добија позив Универзитета у Београду и 1910. године се коначно сели у Србију и добија српско држављанство. Овај чин патриотизма га је одвео у заробљеништво током Првог светског рата који је у почетку провео у логору, али му је након ургенције бивших професора омогућено да остатак рата проведе у кућном притвору у Будимпешти бавећи се научним радом. Тада се родила и идеја о теорији климатских промена која је публикована 1920. године. Она заједно са другим његовим капиталним делом „Канон осунчавања“ представља једно од најзначајнијих научних достигнућа икада.

Пријатељство са другим великим заљубљеницима у геологију Вегенером и Кепеном довело је до изузетно значајних открића везаних за геонауке. Најзначајнији утицај његовог рада се може наћи у циклостратиграфији (прецизна астрономска временска скала), теорији континенталног дрифта и палеоклиматологији. Након добрих резултата прављења астрономске временске скале за кенозојске и мезозојске седименте доста савремених научних студија је посвећено калибрацији палеозојске ере. Поред тога што нам омогућава анализу климатских промена из прошлости Миланковићева теорија служи и као основа за прављење прогнозних климатских модела. Ови модели омогућавају боље разумевање разлога настанка климатских промена као и значаја и количине утицаја човека на њих.

Миланковић представља савршен узор за младе научнике и пример како одлучност и љубав према науци доводе до изузетних научних резултата упркос тешким условима. Поред тога, он је сигурно најзначајнији српски научник који је највећа научна достигнућа постигао живећи и радећи у Србији.

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