



Association Milutin Milanković Belgrade

Proceedings of the Online Symposium

**MILUTIN MILANKOVIĆ:
THE PAST 100 YEARS,
AND THE FUTURE**

Belgrade, Serbia
2020

**Proceedings
of the Online Symposium**

**MILUTIN MILANKOVIĆ:
THE PAST 100 YEARS, AND THE FUTURE**

Commemorating the centenary of the publication
*Théorie mathématique des phénomènes thermiques produits
par la radiation solaire*

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For the publisher

Slavko Maksimović

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Consultant

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Editors

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Milutin Milanković



28 May 1879 – 12 December 1958

The beginning of the life story of Milutin Milanković is on 28 May 1879 in Dalj, a place at the banks of the Danube, in the vicinity of Osijek, the then capital of Slavonia, one of the southern provinces of the Habsburg Monarchy. Due to its size and flow, the Danube became an obsession of time and space for Milanković. The river near which he spent his whole life gave him the necessary security in life, in it he found sources of inspiration for his creative work.

Milanković completed his secondary education in Osijek. He continued his education in Vienna at the Technical High School. He completed his studies in civil engineering in 1902, and defended his doctoral dissertation on 3 December 1904, at the age of twenty five.

For Milanković, Vienna was a place of growing up and turning into a mature man and scientist. It was a meeting place of the scientific elite of the whole of Europe of the time and a centre for the exchange of scientific thoughts, which young Milanković used extensively to acquire a broad education.

Although a civil engineer by education, a university professor of celestial mechanics by profession, Milanković, with the strength of his talent, but above all with persistent and systematic work, expressed himself and created in various scientific disciplines and fields. Construction mechanics and civil engineering, astronomical theory of climate change, calendar reform, popular science works and the history of natural sciences are the areas in which Milanković's scientific thoughts are reflected.

He had a very successful career as a civil engineer in Vienna, but his wish was to become a professor at a university, because there he could dedicate himself completely to scientific work.

In 1909, he accepted an invitation from the Faculty of Philosophy of the University of Belgrade, which offered him a position as a lecturer at the Department of Applied Mathematics, which included rational mechanics, celestial mechanics and theoretical physics.

Having chosen the climate of the distant past as the subject of his scientific research, he carefully planned his scientific journey through the "distant worlds and times". That journey he set out on will last for a full thirty years.

One of Milanković's stops on his journey through the "distant worlds and times" was Budapest, where he spent the First World War (1914–1918) in internment as a Serbian citizen. As an already established scientist, he was enabled to work unhindered in the libraries of the Hungarian Academy of Sciences and the Central Meteorological Institute. The results of his four-year work are presented in the book "Mathematical Theory of Thermal Phenomena Caused by Solar Radiation", which was published in Paris in 1920. In it, Milanković presented the basics of the astronomical variations of solar energy and their connection with climate change on the planet Earth. The results of this research were the foundation of his world-renowned theory of climate change.

Milanković continued his work on the development of the theory of climate change in cooperation with one of the world's most famous climatologists, Wladimir Köppen and his son-in-law, a well-known geophysicist, Alfred Wegener. After four years of successful cooperation in their voluminous work "Paleoclimatology" in 1924, Milanković's insolation curves, later known as "Milanković's cycles", were published. With this, it can be considered that Milanković's work on the development of his theory of climate change was completed.

In 1941 Serbian Academy of Sciences printed 600 copies of Milanković's major work "The Canon of Insolation and the Ice Age Problem". It contains his entire long-term work and all the results of his work on the theory of climate change. This work ranked among the most important scientific works of the 20th century. NASA outlet in a 2002's edition of

its series “On the Shoulders of Giants” included Milutin Milanković as one of the 15 “giants” of the Earth sciences.

In 1923, the Congress of Eastern Orthodox Churches was held in old Constantinople, today's Istanbul, at which Milanković's proposal to reform the Julian calendar was accepted, in which the calendar year differs by only 2 seconds from the current length of the tropical year.

Milutin Milanković was not only a scientist, but also a historian of natural sciences, a chronicler of scientific events of his time, a writer of popular science and literary works. He described different times, places of events, vividly and clearly presented the lives of great scientists, and the most complex problems of science for the time in which they were born.

The end of the life story about Milanković is in his native Dalj, on the bank of the Danube - the paradise river Fison, from where he set out on a journey through his "distant worlds and times".

Slavko Maksimović



André Berger



Daniel Schertzer



Denis Dider
Rousseau



Michael Ghil



Jörn Thiede



Hans Peter
Nachtnebel



Ioulia
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Stela Filipi Matutinović



Vlado Milićević

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**Report on the events honouring 100th anniversary of the publication
of Milutin Milanković's book**

*Théorie Mathématique des Phénomènes Thermiques Produits par la
Radiation Solaire*

The year 2020 marked the centenary of the publication of Milutin Milanković's book "Mathematical Theory of Thermal Phenomena Caused by Solar Radiation"¹ in Paris. In this book Milanković presented the basics of the astronomical influence of solar energy on the climate change on the planet Earth. His research resulted in a theory of climate change, later generally accepted in the world. The book was written by Milanković during his internment in Budapest during the First World War (1914–1918). Milanković's research in that period was enabled by a warm welcome at the Hungarian Academy of Sciences and the Central Meteorological Institute in Budapest, Hungary. Mr. Szász Domokos, a member of the Hungarian Academy, stated: "*They left him to think and work. Can any scientist wish for more?*"²

The publication of this book had a turbulent prehistory. Milanković completed the book in German under the title "Mathematical Fundamentals of Cosmic Radiation"³ in Mid-1917. He sent the manuscript to Vienna to his professor of mathematics, Emanuel Czuber, for evaluation. Czuber wrote a review of the manuscript and sent it to the publisher of his books (B. G. Teubner in Leipzig, Germany) for printing. B. G. Teubner, at that time the leading publishing company for books of mathematical content, included Milanković's manuscript in the list of its next editions. However, when it was Milanković's turn in early 1918, the publisher could not print it because they ran out of the printing paper. Thus, at the beginning of 1919, Milanković returned to Belgrade with the manuscript of his unpublished work.⁴

Milanković sent the manuscript to his high school professor and member of the Yugoslav Academy of Sciences and Arts from Zagreb Vladimir

¹ Théorie mathématique des phénomènes thermiques produits par la radiation solaire

² Szász Domokos, at the time Vice President of the Hungarian Academy of Sciences

³ Mathematische Grundlagen der kosmischen Strahlungslehre

⁴ A manuscript copy of this seminal work by Milanković is in the Library of the Hungarian Academy of Sciences in the collection of valuable manuscripts

Varićak, who jointly with the well-known Croatian geophysicist Andrija Mohorovičić wrote and submitted its review to the Academy. The Academy decided to publish the manuscript as a separate edition, but translated into French. That is what the political circumstances at the time demanded, Milanković stated. The book was translated to French by Milanković and Ivan Djaja.⁵

Funds for printing the book were provided by the Ministry of Education of the Kingdom of Serbs, Croats and Slovenes. In agreement with the well-known publishing house Gauthier-Villars from Paris, which was the official publisher of educational and scientific institutions in Paris, namely, the *Ecole Polytechnique* and the *Bureau des Longitudes*, the Yugoslav Academy of Sciences and Arts organized the printing of the book in the Zagreb Archdiocesan Printing House. The book was published in the fall of 1920.

Printed copies of the book were delivered to the publishing house Gauthier-Villars, which included the book in the catalogue of its publications, sent a number of copies to scientific journals for reviews, to scientific institutions for their libraries, and to some scientists as a gift.

The book generated great interest of the scientific public of the time. Milanković's explanation: *"The first echoes and reflections of my work in the public began to arrive in my scientific workshop. As early as 1921, I read in one of the weekly "Reports of Sessions" of the French Academy that its permanent secretary drew the attention of those present to my work. In the same year, the German "Meteorological Journal" published an extensive review of my work, and during the printing of the fourth edition of Hann's "Textbook of Meteorology", the results of my research into the Earth's solar climate was included in this great work.*

Those reflections shed their light on my overall research as well. But, knowing the history of science well, I knew that it did not mean the light of day. Many scientific achievements, far more extensive than mine, have been waiting for full recognition and acceptance for years and decades.

⁵ Ivan Djaja was born in Le Havre, France. He was married to a French lady and after finishing his studies he came to Belgrade, where he was elected assistant professor of Physiology at the Faculty of Philosophy. He raised that science to a high level and became one of the most famous names of the University of Belgrade.

And I also knew that if my work is a real scientific contribution, it will find its way without anyone's help, recommendations and praise.”

Certainly, Milanković was right. After the theory was published, a discussion arose about its validity. Fierce debates lasted for a full 50 years. The theory was finally proved by American and English scientists Hays, Imbrie, and Shackleton, who used the modern spectral analysis for studying undisturbed sediments as traces of ice ages from the ocean floor, almost 20 years after Milanković's death.⁶

Milanković's research on climate change published in this book can be considered a precursor to the modern knowledge about natural factors that trigger and affect climate change.

With this masterpiece, which crowned his ten-year scientific efforts, Milanković opened hitherto inconceivable views in the field of studying the climate of the distant past. He was the first to mathematically establish a connection between the insolation and the temperature of the atmospheric layers and provide background for studying the centuries-old changes in the Earth's climate.

The Association Milutin Milanković, in consultation with prominent experts in the field of climate change and a number of scientific and educational institutions from Serbia and other countries, launched an initiative to mark this important jubilee. The program was jointly prepared by institutions and individuals from Serbia, where Milanković worked, Austria, where he was educated, Hungary, where the book was written, and France, where the book was published.

It was planned that the initial parts of the program, before the main event in Belgrade, would be organized in Vienna, Budapest and Paris, where exhibitions, promotional lectures, video projections, working meetings of experts, and other appropriate activities would be carried out. It was planned for program to end with a Jubilee celebration gathering and a high-level experts scientific/professional symposium in Belgrade under the auspices of the Ministry of Environmental Protection of the Republic of Serbia.

⁶ John Imbrie and Katherine Palmer Imbrie: *Ice Ages-Solving the Mystery*, Enslow Publishers, Short Hills, New Jersey. 1979, 224 pp.

Due to the pandemic situation caused by the COVID-19 virus, unfortunately, the implementation of the planned activities were adjusted to the prescribed health protection measures, thus some, already prepared activities, had to be canceled.

In compliance with all the prescribed health protection measures, the Jubilee celebration took place on November 17, 2020, at the Rectorate of the University of Belgrade. A scientific/professional online symposium, coordinated from the headquarters of the Association Milutin Milanković, was held on November 18, 2020.

At the Jubilee gathering,–the Rector of the University of Belgrade, Prof. Ivanka Popović and Academician Fedor Mesinger spoke about Milanković's pedagogical and scientific work at the University and the Serbian Academy of Sciences and Arts, as well as his scientific contribution to world science and human civilization. On behalf of the foreign participants Prof. Daniel Schertzer from the French university *Ecole des Ponts Paris Tech (ENPC)* – program coordinator in France – delivered his video-message. The documentary "The Birth of Climate Change Theory" was presented to the public for the first time. The complete program was recorded and the footage or its selected parts is available from the organizers.

In the scientific/professional symposium, 24 papers of invited experts from 11 countries (France, Hungary, Austria, Canada, Belgium, Great Britain, the Russian Federation, the USA, Brazil, Montenegro and Serbia) were presented, among which were the world's leading climate-change experts, and followers of Milutin Milanković's work. A number of participants followed the Symposium online.

The papers presented at the Symposium covered both natural and anthropogenic causes of climate change. The papers were clustered in 2 groups: (a) the significance of Milanković's theory and the results of new research, covering the period of the past 100 years; (b) natural and anthropogenic climate change expected in the next century and possible measures to prevent or reduce its negative impacts.

The organizers of the Symposium accepted the suggestions of participants to do the following:

- post the presented papers and presentations on the website of the Association Milutin Milanković (www.milutinmilankovic.rs);
- publish Proceedings of the Symposium in both, electronic and printed form;
- inform the interested scientific, educational, professional and the relevant state institutions in Serbia on the recommendations of the Symposium and invite them to take an active role in creating action plans for mitigation of both short term and long-term climate change detrimental impacts.
- encourage the authors of the presented papers to upgrade and submit those papers for publication in renowned international journals, e.g. the joint special issue of “Nonlinear Process in Geophysics” and “Climate of the Past”, both published by European Geophysics Union (EGU) (coordinators Prof. Daniel Schertzer and Denis-Didier Rousseau)
- organize a similar event dedicated to the more recent research complementary to Milanković's work (coordinator André Berger).

In addition to marking Milanković's contribution to the world science and civilization by the Symposium, several complementary programs were realized to create a permanent legacy based on life and work of Milutin Milanković:

- a memorial plaque was placed on the building of the Rectorate of the Belgrade University, celebrating the decision of the European Association of Physicists to declare the University of Belgrade (the place of Milanković's climate research), a historical site (EPS Historical Site) of importance for the development of physics sciences;
- a reprint of Milanković's book published in Paris in 1920 was produced;
- a bilingual booklet "Milutin Milanković and his Scientific Opus from a Scientometric Perspective" by Dr. Stela Filipi-Matutinovic was published in Serbian and English;
- documentary "Making a Theory of Climate Change" was produced.

The organizer of the Jubilee events/program, the Association Milutin Milanković, provides to all participants the following:

- Proceedings of the Symposium in electronic and printed form;
- A Serbian-English publication "Milutin Milanković and His Scientific Opus from a Scientometric Perspective" by Dr. Stela Filipi-Matutinović;

- Anniversary reprint of the Milanković's book: *Théorie Mathématique des Phénomènes Thermiques Produits par la Radiation Solaire*;
- Documentary "Making a Theory of Climate Change".

Acknowledgements

The Association Milutin Milankovic is thankful to the participants of the scientific-professional symposium, institutions and individuals who, through their support and assistance, contributed to the success of the Jubilee. We owe a special thanks to:

- The Ministry of Environmental Protection of the Republic of Serbia, the sponsor of the celebration;
- The Centre for the Promotion of Science, Belgrade, a partner in the celebration;
- A number of faculties at the University of Belgrade: Civil Engineering; Mathematics; Mining and Geology; Forestry, as well as two co-organizing institutes: The Institute for Biological Research "Siniša Stanković", and The Institute for Water Management "Jaroslav Černi";
- Members of the Scientific and Organizing committees of the Association Milutin Milanković;
- Dr. Stela Filipi-Matutinović for preparation, publication and making her book "Milutin Milanković and his Scientific Opus from a Scientometric Perspective" available to the participants;
- Prof. Daniel Schertzer for organization of the publication of selected peer-reviewed papers from the Symposium in joint special issue of two journals of the European Geosciences Union;
- Professors Zoran Stevanović and Čedo Maksimović for exceptional devotion and engagement in defining program activities and organizing the Symposium, as well as for successfully moderating Symposium sessions;
- Professors Daniel Schertzer, André Berger and Fedor Mesinger, in addition to their valuable help with their own scientific contributions to the realization of the Jubilee, for their inspired address ("*words of wisdom*") to participants at the opening of the gathering at the Rectorate of the University of Belgrade and at the end of the Symposium.

Slavko Maksimović
President of the Association Milutin Milanković

**Part I: Milanković's theory and impact on
understanding of climate change**

MILANKOVITCH, THE FATHER OF PALEOCLIMATE MODELLING

ANDRÉ BERGER

*Georges Lemaître Center for Earth and Climate Research, Earth and
Life Institute, Université catholique de Louvain, 1348 Louvain-la-Neuve,
Belgium*

E-mail: andre.berger@uclouvain.be

Abstract. The origin of the long-term variations of the astronomical elements used by Milankovitch are first described, followed by the value of the astronomical periods. The detailed calculations by Milankovitch of the incoming solar radiation during the astronomical and caloric half-years are summarized, stressing the originality of the caloric ones. The second original contribution of Milankovitch to paleoclimate research was without any doubt his mathematical climate. How this model allowed him to give the caloric summer and winter insolation a climatological meaning is illustrated.

Key words: Milutin Milankovitch, History of science, Climatology, Astronomical theory, Paleoclimates, Caloric seasons, Climate model

1. INTRODUCTION

Paleoclimatology is primarily a reconstruction of past climatic variations on the basis of proxy records. It aims also to explain these variations from principles of climatic behaviour using climate models. Milankovitch has contributed significantly to this second objective by using the astronomical parameters to compute the long-term variations of his caloric insolation which he used in a climate model (although very simple) to reconstruct the past climates. This paper intends to underline the fundamental and original contributions of Milankovitch in the understanding of the long-term climatic variations over the last one million years.

The two remarkable books of Milutin Milankovitch, his 1920 *Théorie Mathématique* written in French and -his 1941 *Kanon der Erdbestrahlung* written in German and translated in English in 1969, have largely contributed to his reputation. The celebration of the 100th anniversary of

his 1920 French book is a good opportunity to stress what were his main contributions and to “rendre à César ce qui appartient à César (give back to Caesar what belongs to Caesar)”. There is indeed a tendency to over-inflate one’s work for reasons that have nothing to do with the scientist, but for reasons that have to do with corporative or national politics of history of science. It is important to stress here that Milankovitch was always very careful through all his publications referring properly to the publications of others when he was using their results.

2. LONG-TERM VARIATIONS OF THE ASTRONOMICAL PARAMETERS

Contrary to what might be thought, Milankovitch has not calculated himself the long-term variations of the astronomical elements. He used them extensively for calculating the “secular march” of the incoming solar radiation.

The first to calculate these astronomical elements was the French astronomer Joseph-Louis Lagrange (1736-1813). He made the calculation for the six great planets (1781-1782). At that time, Uranus was only going to be discovered and the mass of the planets could only be roughly estimated. Aware of this uncertainty on the masses, Lagrange investigated its possible influence on his calculations, a formulation that was going to be used more than one century later by Vojislav Miskovitch (1892-1976), a colleague whom Milankovitch solicited his collaboration.

During the early 19th century, Pierre-Simon Laplace (1749-1827) wrote his 5-volume *Celestial Mechanics* between 1799 and 1825. Philippe Gustave le Doulcet, Comte de Pontécoulant (1795-1874) carried out the computation of the long-term variations of the elements of the great planets but with a few decimals only.

It is during the second part of the nineteenth century that Urbain Le Verrier (1811-1877) came with a new theory of the planetary motion (1855) and the calculation of the secular perturbations (1856). He published the numerical values of eccentricity (with a precision of 10^{-4}), longitude of the perihelion (in arc minutes), inclination (in arc seconds) and longitude of the node over 100,000 years before and after 1800 A.D. each tenth millennium. His calculations were carried out before he discovered the planet Neptune. As this planet could not therefore be included in the Le

Verrier calculations, John Nelson Stockwell (1832-1920) computed the secular perturbations by considering all the eight planets known at his time (1873): Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus and Neptune. Stockwell, as Le Verrier, had the possibility of correcting his computations by using better values of masses. This work completed the calculations of the secular perturbations of the great planets, but an error was discovered by Harzer (1895) twenty-two years later. Finally, it is the German Ludwig Pilgrim (1879-1935) (known mostly as a pioneer in colorimetry) who computed, at a time when Milankovitch was completing his doctoral degree thesis in 1904, the astronomical elements requested for the computation of insolation. Pilgrim extended (Pilgrim, 1904) the numerical computations of eccentricity, obliquity and longitude of the moving perihelion, using the Stockwell integrals for every fifth millennium over 1,010,000 before and 40,000 years after 1850 A.D. and also for dates where the longitude of the perihelion was either 90° or 270° (Northern Hemisphere summer at aphelion or at perihelion). In Milankovitch's own words, Pilgrim was the first to compute adequately the elements affecting the long-term variations of insolation, so that Milankovitch could use them for his research. Pilgrim tried also to treat the Ice Age mathematically, but according to Milankovitch, this treatment of the climatological part by Pilgrim was a failure.

Milankovitch clearly indicates that for the calculation of his incoming solar radiation (insolation in short), he used first Stockwell-Pilgrim's values of the eccentricity, obliquity and precession for the last 1,000,000 years before 1850 A.D. The numerical values of these astronomical parameters were reproduced in his 1920 book for the last 500,000 years. The insolation values for 55° , 60° and 65° N were published in Köppen-Wegener (1924) before the calculation was extended to other geographical latitudes and the new values published in his *Mathematische Klimalehre* in 1930.

Because of some errors in Stockwell (already detected by Harzer) and because he wanted to use the astronomical parameters based on the most reliable values of the planetary masses, Milankovitch decided to use the Le Verrier calculation including his corrections for the masses. For completing this work, he asked the collaboration of his colleague, Prof V. Miskovitch (1892-1976). Miskovitch made the necessary corrections of the masses following Le Verrier procedure and computed the long-term variations of eccentricity e , obliquity ε , and climatic precession $e \sin \pi$, (π ,

the longitude of the perihelion) for the past 600,000 years before 1800 A.D. with the following initial values:

$$e_0=0.0168 \quad \pi_0=99^{\circ}30' \quad \varepsilon_0=23^{\circ}27'55''$$

All these values were published in *Mathematische Klimalehre*, 1930 and in *Astronomische Mittel* in 1938 and reproduced in Table IX of his Canon. Milankovitch carefully noticed that the Hungarian scientist von Bacsàk (1870-1970) draw his attention to two calculation errors, both related to $\Delta(esin\pi_0)$, one at 500 ka BP and the other at 465 ka BP, errors that Milankovitch took care to eliminate from his tables.

This use of two different astronomical solutions explains why we find in the early work of Milankovitch the astronomical values of Stockwell-Pilgrim and in his later work the values of Le Verrier-Miskovitch. The comparison of the insolation values that Milankovitch calculated from these solutions show a good agreement. Milankovitch concluded that a further improvement of the planetary masses using the formulation by Le Verrier would not change “the essential features of the secular course of insolation as I have calculated”.

Milankovitch was however well aware that the solution by Le Verrier could not be extended over millions of years because of the limited accuracy of the perturbation calculation that was based upon classical mechanics, missing the Einstein relativistic displacement of the perihelion of the planets.

3. PERIODS OF ASTRONOMICAL PARAMETERS

Milankovitch calculated with great details the incoming solar radiation on the Earth, but seemed to have not been much interested in the astronomical periodicities themselves. From his table (based on Stockwell-Pilgrim), he simply deduced the average period of the oscillations of eccentricity as being 92 kyr, varying between 77 and 103 kyr. For precession, he found an average period of 21 kyr, varying between 16.3 kyr and 25.8 kyr. For the longitude of the moving perihelion, he explains that its irregularities are due to the longitude of the fixed perihelion, but whether the perihelion has a mean motion remains an open question. For obliquity, he noticed that it “oscillates between extremely narrow limits” with a relatively stable period of 40 kyr varying between 38 and 45 kyr. It is actually the

French mathematician Joseph Alphonse Adhémar (1797-1862) who was the first in 1842 to deduce the value of 21,000 years for precession by combining the astronomical precession calculated from the value of 50.1" per year of the French astronomer Jean-Baptiste Joseph Delambre (1749-1822) and the rotation of the terrestrial orbit calculated from the value of 11.83" per year of the French mathematician Louis Benjamin Francoeur (1773-1849).

The harmonics of precession, in particular those with a period of 19,000 and of 23,000 years – also found by Hays et al. (1976) in their geological data -, and the 400,000-year of eccentricity were discovered by Berger (1973, 1978a) who calculated all the periods in the expansion of the long-term variations of the astronomical variables used in the calculation of insolation. It is worth to note that Milankovitch was very much interested by obliquity. One of the reasons is probably the strong obliquity signal in his caloric half-year insolation (see Figure 1). Milankovitch mentioned many times that the authors who were mainly stressing precession, were not sufficiently or not properly taking into account obliquity. Tables XII and XIII of his Canon give the change of the radiation of his Table XI for an increase of the obliquity by one degree (respectively in canonic units and in percent). These three tables were first published in his “The Problem of the Astronomical theories of the Ice Ages” in 1914 showing in details for the first time the influence of obliquity upon insolation. To put it briefly, an increase of obliquity reduces the latitudinal contrast between the equator and the poles mainly in the annual irradiation and increases the seasonal one (with an augmentation of the summer irradiation and a reduction of the winter one), with a similar effect in both hemispheres.

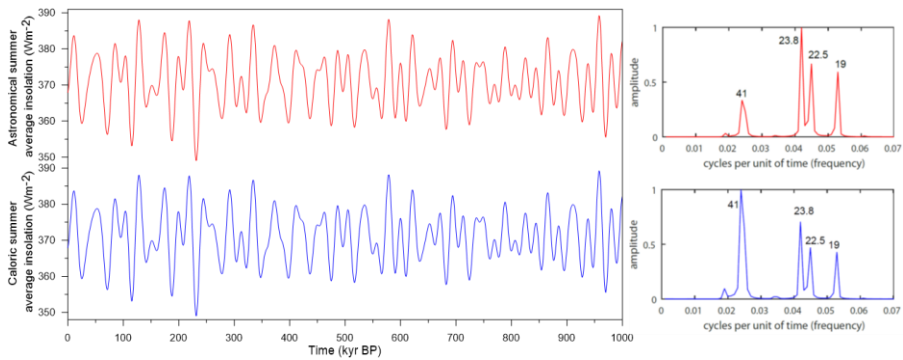


Figure 1: Average insolation of the half-year astronomical (red) and caloric (blue) summer seasons and their spectra (based on Berger and Loutre, 1991 and Berger et al., 2010). The major periodicities in kyr are indicated.

In fact, it is not widely known that similar insolation computations were actually already done in the 19th century by the English Sir John Frederick William Herschel (1792-1871) (published in 1832 for the total irradiation), by the American scientist Levi Witter Meech (1821-1912) (published in 1856 for the daily and seasonal irradiation at any latitude based on elliptical integrals), by the German mathematician Ludwig Christian Wiener (1826-1896) (published in 1877, he did the same as Meech with in addition the total irradiation over different parts of the Earth) and by the Irish intellectual Joseph John Murphy (1827-1894). It was actually Murphy who was the first in 1869 to put forward the idea that a long, cool summer and a short, mild winter are the most favourable conditions for glaciations (a hypothesis totally opposite to Croll, 1864). This idea was taken up by the Austrian climatologist Rudolf Spitaler (1859-1946) half a century later (in 1921). It does therefore follow that it is not Milankovitch who originated this principle as some authors have claimed and still claim calling it the “Milankovitch model”. Milankovitch has actually popularized and spread the idea under the advice of Köppen (1941) who claimed: “the diminution of heat during the summer half-year is the decisive factor in glaciation” and also following the comments made earlier by Penck and Brückner (1909) and Bruckner et al. 1925: “From the climatological point of view, glaciers are not favoured by severe winter...but by a mild winter and a cool summer”.

4. CALORIC SEASONS

When dealing with the astronomical seasons, the long-term variations of both their total irradiation and of their length must be taken into account. To avoid this difficulty, Milankovitch introduced the caloric seasons. This concept of caloric seasons is one of the two most important and original contributions of Milankovitch. These divide the year into two equally long seasons, one of which – the caloric summer – comprises all days during which the irradiation at the given latitude is stronger than on any day of the other half-year – the caloric winter. Because the semi-major axis of the Earth's orbit, the sidereal period of revolution of the Earth around the Sun and, to an excellent approximation, the tropical year do not change with time, the length of these caloric seasons is exactly 182.6211 mean solar days when the tropical year is used. This, however, does not solve the problem completely because the origin and end of these half-year seasons change with time and because the double maximum and minimum characterizing the insolation in the intertropical regions.

Milankovitch noticed that he discovered these caloric seasons after his 1920 book on “Théorie mathématique” was published and used them for the first time in his contribution (*Mathematische Klimalehre*) to the 1930 Köppen-Wegener Handbook.

In his Canon (1941), Milankovitch devoted twenty pages to the “quantities of heat received by a latitude during a caloric summer and winter half-year”. From the formulas that he developed, it is clear that, during their local season, the impact of the variations of obliquity is the same in both hemispheres and maximum in the high latitudes, whereas the impact of climatic precession is opposite in the two hemispheres and maximum at the low latitudes.

In Chap. XX of his Canon, Milankovitch gave the numerical values of the caloric Northern and Southern hemisphere summer half-years for 1800 (Table XXIII) and over the last 600,000 years (Table XXV) in canonic units (the canonic units introduced by Milankovitch are the units obtained if the solar constant is the unit of solar radiation and if the unit of time is 100,000 instead of seconds). Since no hypotheses were introduced for these calculations, Milankovitch convinced of the perennity of his work

decided to call his results “Kanon der Erdbestrahlung” (Canon of Insolation).

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°N equivalent latitudes; this was first published in his *Mathematische Klimalehre*. These latitudes are actually the present-day latitudes, which received during the Northern Hemisphere caloric summer half-year the same irradiation than 65°N in the past. A fictitious motion of these latitudes to the south corresponds therefore to an increase of the summer irradiation.

5. THE MATHEMATICAL CLIMATE

It must be stressed that the main contributions of Milankovitch were not only based on his insolation and radiation curves, but also on his mathematical computation of the thermal effects of the secular march of insolation, his so-called mathematical climate. The direct effect calculated if insolation only was varying was published in his 1930 *Mathematische Klimalehre*. From the Stefan law and a grey body model with the reflective power of the surface and the absorption coefficient in IR kept invariable, Milankovitch calculated the long-term variations of the mean temperatures of the caloric summer and winter half-years ($\Delta T = \Delta Q / 150$, ΔQ in canonic units).

If the ice cover and other feedbacks are taken into account, the indirect effects could be estimated. This was published in 1938 *Astronomische Mittel* where Milankovitch calculated first the altitude of the snow limit H_i , as a function of the caloric summer insolation. This calculation was based on the correlation between these variables according to Köppen snow limit data for different latitudes. According to his relationship, any variation of the summer irradiation by 1 canonic unit produces a shift of the snow limit altitude by 1m ($\Delta H_i = 1.09 \Delta Q_s$). These relationships allowed Milankovitch to give the caloric summer and winter insolation a climatological meaning. This shows how much he was concerned by climate and its variations. As these relationships are simple and straightforward, Milankovitch did not publish any additional tables and referred only to his tables providing the long-term variations of the caloric summer and winter half-year insolation. From his Table XXV, we can see that the deficit in summer radiation can reach 573 canonic units at 75°N,

22100 years ago, which according to his formula means a drop of the altitude of the snow line by more than 500m. Following the Köppen table of the altitude of the snow limit for different latitudes, the polar cap can then have extended from 75°N up to 65°N, it means covering an area 2.75 greater. This kind of deficit can also be reached in the tropical latitudes with an accompanying lowering of the snow limit altitude which, as noted by Milankovitch “refutes the opinion expressed by some geologists that insolation cannot explain such displacement”. Milankovitch also pointed out that “owing to such variations of the summer irradiation, the mean summer temperature dropped from time to time by more than 5° in the high and temperate latitudes of both hemispheres and even in the tropical latitudes”.

6. IRRADIATION OVER THE POLAR CAPS

Most important is that such an increase of the size of the polar snow cover changes the reflective power of the Earth. This is why to complete his Kanon, Milankovitch decided to compute the long-term variations of the mean summer and winter insolation per unit surface area of the Northern and Southern polar snow-caps over the last 600,000 years (Table XXVIII). The extent of these polar caps was deduced from the treatise by Wundt (1933). In this treatise, the Northern cap extends presently to 75°N and reached 55°N at the maximum of the Ice Age. From these values, Milankovitch could compute the long-term variations of the insolation over such polar caps delimited by the parallel 55° assuming that the extension of the snow cap was always proportional to the corresponding deficit in summer radiation. If the albedo is kept constant, it can be seen that the minimum summer radiation over the Northern cap reaching 55°N occurred 230,000 years ago, with a radiation deficit $\Delta Q_s = 363 \Delta \epsilon - 7900 \Delta(e \sin \pi)$, compared to the present, amounting 660 canonic units (ϵ is the obliquity, e the eccentricity and π the longitude of the perihelion). As this deficit caused a southward extension of the cap of 20°, Milankovitch concluded that a change by one canonic unit corresponds to a meridional change in the extent of the Northern polar cap by about 1'82 or 3.37 km. This means also that the Northern snow cap totally disappears for an increase of the summer insolation by 495 canonic units. This occurred quite a few times over the last 600,000 years, as for example 10,000 and 127,000 years ago.

Taking into account the reflective power of snow at the Earth' surface, for the cap reaching 55°N

$$\Delta_2 Q_S = 0.802(13520 + \Delta_1 Q_S) [\sin(75^\circ + 1'82\Delta_1 Q_S) - \sin 75^\circ]$$

shows that large negative amplitudes occurred several times over the last 600,000 years. At 230 kyr BP, the total deficit $\Delta Q_S = \Delta_1 Q_S + \Delta_2 Q_S$ amounts now 2180 canonic units. This is far more than the 660 deficit calculated if the reflective power of snow is not taken into account. It corresponds to a displacement downward of the snow limit of 2180 m which is about the present altitude of the snow limit at 55°N. This implies that the polar cap must have reached this latitude at that time, what according to Milankovitch was actually observed in the geological reconstruction. It is also interesting to notice with Milankovitch that the deficit of the annual radiation at 230 kyr BP amounted 1920 caloric units which means a decrease in the annual temperature by 6.4 °C ($\Delta T_T = \frac{\Delta Q_S + \Delta Q_W}{300}$)

contradicting those who claims that the long-term variations of insolation can not cause any important drop in the annual temperature.

Using the data for the cap reaching 45°N, nine large deficits can be observed at 590.3, 550, 475.6, 435, 230, 187.5, 115, 71.9 and 25 kyr BP. These can be assembled in groups corresponding to the four glacial periods of the Penck-Brückner scheme recognized by Köppen in the Milankovitch 65°N equivalent latitude.

These new results taking into account the reflective power of the polar caps in addition to the long-term variations of insolation were published in "Neue Ergebnissen" (Milankovitch, 1937-1938) and, according to Milankovitch are "absolutely sufficient to explain the full extent of even the greatest climatic events of the Quaternary and to clearly show their causes". All these calculations show clearly that Milankovitch can be named the "father of paleoclimate modelling", certainly more specifically than the father of the astronomical theory in general (the first to propose the variations of the Earth's orbit as the causes of climate changes was Jens Esmark (1763-1839), (Hestmark, 2017), 100 years before Milankovitch). Milankovitch was the first to demonstrate mathematically that the long-term variations of insolation are responsible for the climatic variations over the last hundreds of thousands of years. With his contemporary colleagues, Penck, Brückner, Köppen and Wegener (see

also Thiede, 2018), to cite only a few among the most well-known, he could show that his mathematical climate fits well the geological reconstruction of climate available at these times.

Acknowledgments

Thanks are due to Prof Vladimir Janković from the Center for the History of Science, Technology and Medicine at University of Manchester for his thoughtful comments and his proof-reading suggestions. Thanks also to Dr. Qiuzhen Yin from Université catholique de Louvain for reading the paper and for providing Figure 1.

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SCALING AND MULTIFRACTALITY OF THE CLIMATE RESPONSE TO ASTRONOMICAL CYCLES

DANIEL SCHERTZER
and
IOULIA TCHIGUIRINSKAIA

Hydrology Meteorology and Complexity, Ecole des Ponts Paris Tech
6-8 Av. B. Pascal, 77455 Marne-la- Vallée, France
E-mails: daniel.schertzer@enpc.fr, ioulia.tchiguirinskaia@enpc.fr

Abstract. We start from a profound epistemological question raised by Milanković, that is to say the stark contrast between the regularity of astronomical cycles and the irregularity of the atmospheric response, and we point out this correspond to a fundamental problem of renormalisation when upscaling the system up to climatological scales. We first clarify that two distinct representations of spectral analysis yield two complementary insights, while they appear at first glance opposite. Indeed, we show that both agree on the prevalence of the nonlinearity of the climate response. We generalise this spectral analysis with the help of a multifractal analysis of the Vostok data. This provides evidence of a strong intermittency, in fact nonlinearity in nonlinearity. Therefore, the spectral scaling is clearly generated by nonlinear processes, and out of reach of linear stochastic differential operators.

Key words: Milanković’s cycles, Climate response, Scaling, Multifractals, Nonlinear stochastic modelling

1. INTRODUCTION

In the introduction to his book [1], Milutin Milanković explains his epistemological approach of a system as complex as the climate of the Earth, and in fact of other planets. Not only he mentions that “to handle the mathematical phenomena of nature, it is always necessary to admit simplifications and to neglect certain influences and irregularities. ”He had to do it in front of an object as complicated as our atmosphere”, but more importantly he points out that: “This variable distribution of solar radiation on the surface of the Earth is the primary cause of all meteorological phenomena, whose irregularity singularly contrasts with

the regularity of their primary cause. Meteorological phenomena appear as capricious as the radiation - with which the Sun floods the Earth - follows a regular diurnal and annual course”, i.e., a stark contrast between the regularity of astronomical cycles and the irregularity of the atmospheric response.

This communication is devoted clarifying this contrast, which is not limited to meteorological scales, as underlined by Milanković, but is also relevant for climate scales. We first underline that the basic source of this contrast is due to the strong nonlinearity of geophysical phenomena and that paleoclimatic data could help to assess the nonlinearity level. We then clarify and reconcile two points of view based on two types of “spectral analyses”, both often using this common denomination but addressing different properties of the analysed signal. One of them confirms the prevalence of a scaling response on a large range of scales, but multifractal analysis, which can be understood like a generalisation of the spectral analysis, gives evidence that this scaling is clearly generated by nonlinear processes, not by linear stochastic differential operators, as often hypothesised.

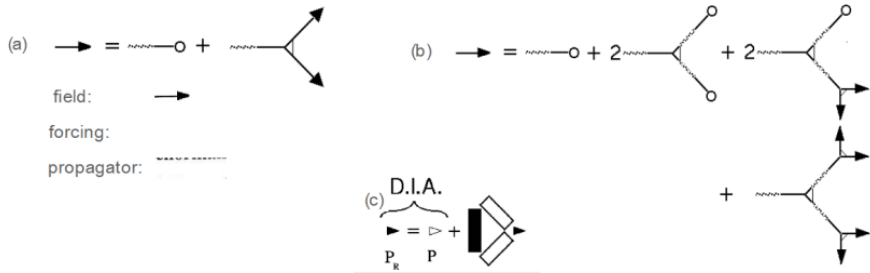


Figure 1: (a) diagram schematically representing a quadratic nonlinear system, where the (black) arrow represents a space-time field of interest (e.g., a vector whose components are various atmospheric fields), the void circle represents a forcing (e.g., astronomical forcing), the half wavy line a propagator (or Green function) that is the inverse of a differential operator (possibly of fractional/non integer order) and the void triangle, which appears as a vertex of this diagram, is the kernel of interactions; (b) first order expansion with respect to the forcing term that illustrates how the nonlinearity generates higher and higher order interactions as soon as the intensity of the original interaction competes with the forcing, and thus prevents convergence; (c) schematic representation of a renormalisation (full triangle), i.e. of the interaction kernel, whereas this not performed in the framework of Direct Interaction Approximation (adapted from [2], [3]).

2. SOURCE OF THE CONTRAST

With the help of diagrams “à la Feynman”, Fig.1 schematically illustrates the complexity of a nonlinear system response to a forcing (e.g., sun radiation) if the intensity of the nonlinear interactions (the vertex of these diagrams) is strong [2] [3] [4]. This schematic is very general and can represent a wide diversity of nonlinear systems, either (apparently) deterministic (e.g., the Navier-Stokes equations, the Lorenz model [5], the Scaling Gyroscope Cascade model [6]) or stochastic (e.g., nonlinear Langevin equations [7]), as well various representations of the same system (e.g., in the physical space and in the Fourier space). The only restriction is that the nonlinearity is initially quadratic, but there is no difficulty to start with higher orders of interactions, which are in any case generated by the expansion (Fig. 1b).

Complexity arises as soon as the intensity of the nonlinear interactions competes or dominates the linear response. For instance, this intensity is estimated with the help of the Reynolds number in fluid flows. Expansions with respect to the forcing then merely do not converge, involving more and more complex diagrams with an increasing number of vertices, therefore stronger and stronger nonlinearities. Nevertheless, one hopes to find appropriate ways to upscale the system to larger and larger time scales in renormalizing the basic components of the system, e.g., eliminating the smaller scales while keeping basic properties of the system. There had been hopes (e.g., the celebrated Direct Interaction Approximation [8], [9]) that renormalising the propagator and the forcing together with the field of interest would be sufficient.

However, it turn out these hopes were vain and missed the key feature of intermittency [10], i.e., that the intensity of the nonlinear interaction is extremely variable in space and time. This means that we need to also renormalize the interaction kernel, i.e., the vertex. Below, we show that paleoclimatic data tend to confirm that this is indispensable for climate modelling. In other words, the climate system is not only extremely variable, but also intermittent. This brings into question various attempts to model climate temperature fluctuations with the help of stochastic linear equations.

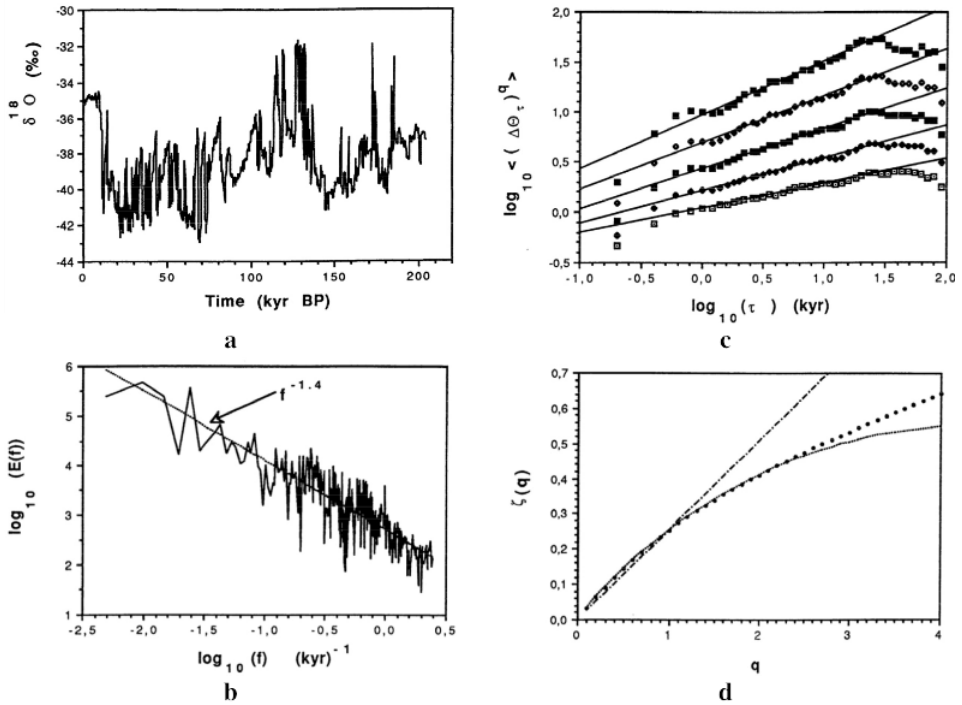


Figure 2: (a) high resolution record of the GRIP isotope ^{18}O fluctuations back to 250 kyr BP; (b) \log_{10} - \log_{10} plot of the power-spectrum $E(f)$ with a scaling/power-law $f^{-\beta}$, $\beta \approx 1.4$; (c) \log_{10} - \log_{10} plot of the structure function $S_q(\tau)$ that exhibits scaling behaviour for $1 \leq q \leq 3$ and $400 \text{ yr} \leq \tau \leq 40 \text{ kyr}$; (d) exponent $\zeta(q)$ of the structure function: empirical curve (dots) close to the semi-analytical curve (continuous), both strongly nonlinear with respect to the structure exponent function $\zeta_{\text{Lin}}(q) = Hq$ (dashes and dots) of a linear fractional process, (adapted from [11]).

3. SPECTRAL AND MULTIFRACTAL ANALYSIS OF THE GRIP DATA

In this section, we recall and illustrate the multifractal methodology with the help of the analysis performed by [11] on the GRIP Greenland ice core [12][13][14]. Figure 2-a displays high resolution (200 year on average) record of the isotope ^{18}O fluctuations, which are considered as a proxy of the temperature fluctuations over 250 000 years. Figure 2-b displays (in a log-log plot) the corresponding power-spectrum that exhibits a scaling/power-law $E(f) \approx f^{-\beta}$, with $\beta \approx 1.4$, over almost all the available frequency (f) range. The authors soberly mentioned that “there is no evidence of periodic variations of frequencies of $(20 \text{ kyr})^{-1}$ or $(40 \text{ kyr})^{-1}$ ”. Below, we will compare this statement to the rather opposite statement of [15] [16]. Before doing this, we will recall the multifractal results obtained by [11] with the help of the structure functions $S_q(\tau)$ of the temperature proxy θ :

$$S_q(\tau) = \langle |\Delta\theta(\tau)|^q \rangle; \quad S_q(\tau/\lambda) \approx \lambda^{-\zeta(q)} S_q(\tau) \quad (1)$$

where $\langle . \rangle$ denotes an ensemble average, $\Delta\theta(\tau)$ the fluctuation of the temperature proxy θ for a given time lag τ and q the statistical order of the structure function.

The second part of Eq.1 corresponds to a scaling behaviour of the structure functions $S_q(\tau)$, where λ is an arbitrary ratio of time scales and $\zeta(q)$ is the scaling function of $S_q(\tau)$. The second order structure function $S_2(\tau)$ is directly related [17] to the power-spectrum $E(f)$ via a Fourier transform and is thus sensitive to quasi-Gaussian fluctuations, whereas $S_q(\tau)$ for $q > 2$ is more sensitive to stronger fluctuations, in fact, to fluctuations of statistical order q . Similarly, $S_q(\tau)$ for $q < 2$ is sensitive to smaller fluctuations. This explains why structure functions can be considered as a generalisation of the spectral analysis.

Furthermore, $\zeta(q)$ would be linear if the process was mono-/uni-fractal, e.g., the process would result from a fractional integration or equivalently satisfy a fractional differential system, therefore be a “linear fractional process”. This is no longer the case if the process results from a nonlinear fractional operator like a cascade process [18][19][20], with the only the pathological exception of the β -model [17]. Figure 2-c provides evidence of the scaling of the structure function $S_q(\tau)$ for $1 \leq q \leq 3$ and $400 \text{ yr} \leq \tau \leq 40$

kyr, whereas Fig. 2-d displays a strong nonlinearity of the exponent $\zeta(q)$ of the structure function. A more careful analysis, which we will not detail here, provides a fit with the scaling function of a universal multifractal [21][22]:

$$\zeta(q) = Hq - K(q); K(q) = C_1 (q^\alpha - q)/(q-1); \beta = 2H+1 - K(2) \approx 2H+1 \quad (2)$$

where the prefactor H of the linear part of $\zeta(q)$ is in fact the fractional order of integration performed by the renormalised propagator, while the nonlinear part $K(q)$ characterises the multiplicative cascade or, in other terms, the renormalised vertex. Let us briefly mention that $C_1 \geq 0$ is the codimension of the mean field and thus measures the mean intermittency of the temperature proxy, while $0 \leq \alpha \leq 2$ measures the variation of the intermittency when observing higher and higher order fluctuations and thus measures the multifractality of the temperature proxy. The case $\alpha=0$ corresponds to the exceptional mono-/uni fractal β -model, which has only a mean field.

The third part of Eq.2 results from the aforementioned relation between the second order structure function $S_2(\tau)$ and the power-spectrum $E(f)$, and the indicated approximation results from the fact that usually that $K(2)$ is much smaller than $2H+1$. For the GRIP data, [11] obtained the following estimates: $H \approx 0.24$, $C_1 \approx 0.05$, $\alpha \approx 1.6$. These estimates provide semi-empirical evidence that the climate response cannot be well represented by only a fractional integration of order H .

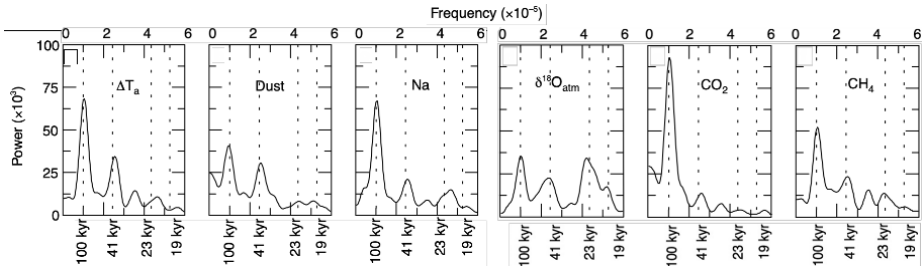


Figure 3: Integrated spectra, i.e. $f E(f)$ vs. $\log(f)$ where $E(f)$ is the power spectrum (see text), of: (a) isotropic temperature; (b) dust; (c) sodium; (d) atmospheric ^{18}O ; (e) CO_2 ; (f) CH_4 . Periodicities of 100, 41, 23 and 19 kyr are indicated by vertical dashed lines (adapted from [15]).

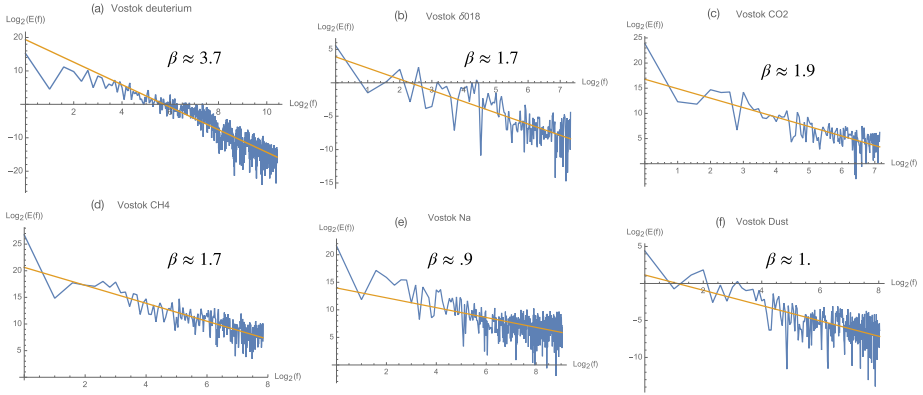


Figure 4: $\text{Log}_2\text{-log}_2$ plot of the power spectra of: (a) deuterium; (b) atmospheric ^{18}O ; (c) CO_2 ; (d) CH_4 ; (e) sodium; (f) dust. Contrary to Fig.3, but similarly to Fig.2b, the astronomical forcing is no longer apparent.

4. SPECTRAL AND MULTIFRACTAL ANALYSIS OF THE VOSTOK DATA

The Antarctica Vostok ice core dataset [15] is very rich since it contains the records of the fluctuations of not only the isotope ^{18}O , but also of the deuterium, sodium, methane, carbon dioxide, dust, ice volume and isotropic temperature over a length of 3,300 m that corresponds to 450,000 year. These data have been extensively analysed, in particular with respect to the Milankovic’s theory. Fig.3 presents the “normalized variance power spectrum (arbitrary units)” of six of these time series. This figure is strikingly different from Fig. 2-b because, contrary to the latter, it exhibits rather clear spectral spikes at 19, 23, 41 and 100 kyr. This spectral analysis is on the contrary in agreement with that of deep-sea cores performed by [16], whose particular importance had been underlined by [23], [24].

Could “spectral analysis” leads to so qualitatively different, not to say opposed, results? Fortunately, this is not due to the involved Fourier transform, the data or the definition of the power spectrum, but simply to two different representation of the latter! Indeed, whereas Fig. 2-b is a log-log plot of the spectrum, i.e. $\log(E(f))$ vs. $\log(f)$, Fig. 3 (adapted from [15]) is a plot of what is often called “an integrated spectrum”, i.e. $f E(f)$ vs. $\log(f)$. The interest of this representation is that the surface under the curve $f E(f)$ for $f_1 \leq f \leq f_2$ and the frequency axis is indeed the integral of the power spectrum over the same frequency interval, i.e. provides the

contribution of each frequency interval to the variance. Although the spikes are well identified on Fig. 3, they are rather broad. This explains why the corresponding log-log representations of the power spectra (Fig. 4) exhibit rather clear scaling laws $E(f) \approx f^{-\beta}$ like Fig. 2b. Figures 3 and 4 in fact displays two different features of a unique dynamics: the climate response is so much nonlinear that it strongly spreads any periodic forcing in the frequency domain and to such a level that periodic spikes are not perceptible on a log-log representation of the power-spectrum (Figs. 2b, 4), but are nevertheless revealed with the help of an integrated spectrum (Fig. 3), which underpins contributions of elementary frequency intervals.

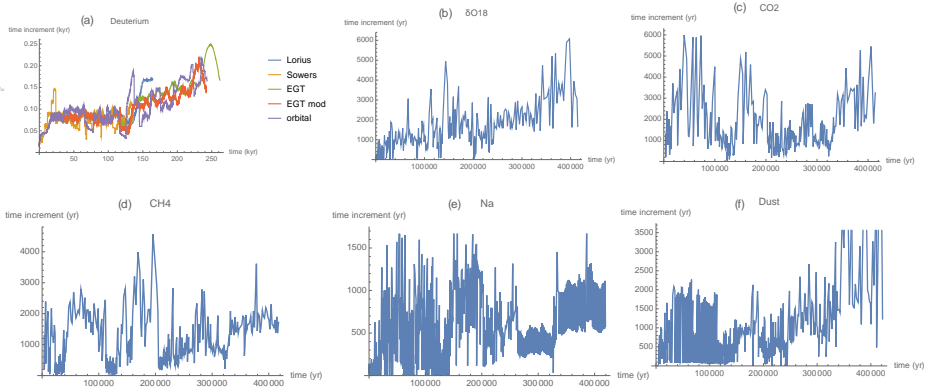


Figure 5: Time series of the estimated glaciological age increments with respect to this age: (a) deuterium; (b) atmospheric ^{18}O ; (c) CO_2 ; (d) CH_4 ; (e) sodium; (f) dust. For the deuterium, five different glacial ages have been estimated by [25], [26],[27] and [28], respectively.

It is timely to note that the glaciological timescale increments of the ice core analysis are far from being regular, as illustrated by Fig. 5, whereas constant ones are required for a Fourier transform. Hence, GRIP data have been interpolated along a linear time scale, but this in turn requires ad-hoc assumptions. So far, no interpolation has been processed on the Vostok data. In both cases, this introduces a given uncertainty.

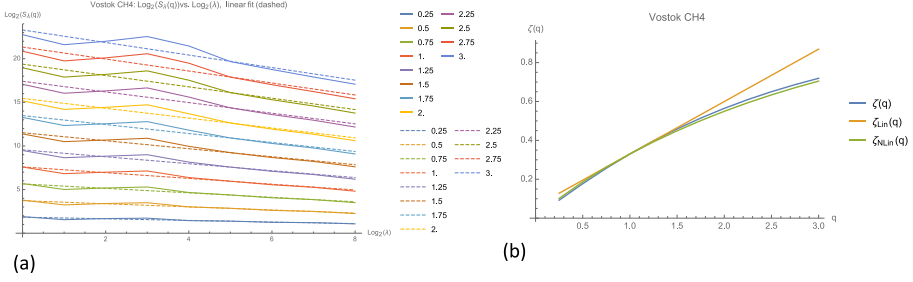


Figure 6: Preliminary multifractal analysis of the methane fluctuations: (a) \log_2 - \log_2 plot of the structure function $S_q(T/\lambda)$, $\lambda=1-2^9$, $T=417$ kyr is the largest time scale; (b) (empirical) structure function scaling exponent $\zeta(q)$ of $S_q(\tau)$ obtained by the slopes of the least mean squares fitting (dashed lines) of $\log_2(S_q(T/\lambda))$ vs. $\log_2(\lambda)$ and which coincides with the semi-analytical $\zeta_{NLin}(q)$ based on the estimates: $H \approx 0.33$, $C_1 \approx 0.06$, $\alpha \approx 1.6$, obtained with the help of the two first derivatives of $\zeta(q)$ (see text, in particular Eq. 3).

Figure 6 displays the two main steps of a preliminary multifractal analysis of the methane fluctuations. Figure 6a displays the \log_2 - \log_2 plot of the structure function $S_q(T/\lambda)$, where the scale ratio λ ranges from 1 to 2^9 , where T is the largest available time scale (417 kyr, the time series being right padded to have a length of power 2) and $\tau = T/\lambda$ is the corresponding time scale over which the temperature increments are averaged. The slopes of the best fitting (least mean squares) of $\log_2(S_q(T/\lambda))$ vs. $\log_2(\lambda)$ of Fig.6a provide an estimate of the structure function scaling $\zeta(q)$ (in agreement with Eq.1). The universal parameters (H , C_1 , α) can be estimated with the help of the relations that follow from Eq.2:

$$H = \zeta(1); \quad C_1 = H - d\zeta(1)/dq; \quad \alpha = -d^2\zeta(1)/C_1 dq^2 \quad (3)$$

This yields the estimates: $H \approx 0.33$, $C_1 \approx 0.06$, $\alpha \approx 1.6$. The goodness of these estimates is illustrated by Fig.6b, where the semi-analytical $\zeta_{NLin}(q)$ based on these parameter estimates is very close to the empirical estimate $\zeta(q)$, as well as the fact that $\zeta_{Lin}(q) = (H - C_1)(q-1)$ is clearly tangent in $q=1$ to both of them. One may note that the value $H \approx 0.33$ satisfies the relation $\beta \approx 2H+1$ (Eq.2) for the methane spectral slope $\beta \approx 1.7$ (Fig. 4d). These estimates also show that the Vostok CH_4 strong multifractality is fully consistent with that of the GRIP data ($\alpha \approx 1.6$), although corresponding to

a slightly higher order of fractional integration and of the mean singularity: $H_{\text{GRIP}}/H_{\text{Vostok}} \approx C_{1,\text{GRIP}}/C_{1,\text{Vostok}} \approx 3/4$.

The consistency of these results emphasises the significance of a renormalisation of the vertex for climate modelling and, in turn, the deficiency of approaches relying only on a fractional integration of order H , which would correspond to $C_1=0$ and $\alpha=0$.

5. CONCLUSIONS

We first highlighted the profound relevance of a key epistemological question raised by Milutin Milanković in his book [1] about climate analysis and modelling: the contrast between the regularity of astronomical cycles and the irregularity of the atmospheric response. We stressed that this contrast is going beyond the meteorological scales and involve indeed climatological scales. We argued this is related to the competition between nonlinearity of the system and linearity of the excitation, which poses a complex problem of renormalisation as soon as the system nonlinearity is strong: the interaction kernel, also called vertex, is also to be renormalized. This is associated with the phenomenon of intermittency: the intensity of interaction is itself strongly fluctuating. We clarified the fact that two distinct representations of spectral analysis yield two complementary point of view, whereas at first glance they appeared as being opposite: one underlines the scaling of the signal, whereas the other one is able to exhibit some traces of the astronomical forcing. We generalised this spectral analysis with the help a multifractal analysis. We thus obtain evidence of strong multifractality and intermittency of paleoclimatic data, confirming that this scaling is clearly generated by nonlinear processes, and out of reach of linear stochastic differential operators.

Acknowledgments

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ABRUPT CHANGES AND THE ASTRONOMICAL THEORY OF CLIMATE?

DENIS-DIDIER ROUSSEAU^{1,2,3} WITOLD BAGNIEWSKI¹ AND
MICHAEL GHIL^{1,4}

¹*Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure,
Paris Sciences & Lettres Research University, Paris, France*

E-mail: denis-didier.rousseau@lmd.ipsl.fr

wbagniewski@gmail.com

ghil@lmd.ipsl.fr

²*Lamont-Doherty Earth Observatory of Columbia University, NY, USA*

³*Geosciences Montpellier, University of Montpellier, CNRS,
Montpellier, France*

⁴*Department of Atmospheric and Oceanic Science, University of
California at Los Angeles, USA*

E-mail: ghil@atmos.ucla.edu

Abstract. The past 3.2 Myr have seen drastic climate changes with the development, waxing and waning of huge continental ice sheets over the Northern Hemisphere. These striking phenomena have been observed in various records from ice cores, as well as marine and terrestrial sediments. These proxy records showed periodicities associated with the three orbital parameters that affect our planet's insolation, namely eccentricity, obliquity and precession. Until recently, these periodicities were considered as the canonical ones for the Quaternary Period and beyond. However, the improvement of the time resolution of available records has allowed one to describe climate changes occurring abruptly and with periodicities that are not related to those of the orbital parameters. In this paper, we show that, in fact, these abrupt climate changes may still be related, albeit indirectly, to the astronomical theory of climate.

Key words: Abrupt climate changes, Astronomical theory, Ice sheets, Dansgaard-Oeschger events, Bond cycles

1. MOTIVATION AND FINDINGS

Abrupt climate changes constitute a new field of research, which addresses fluctuations that occur in a relatively short time interval of some tens of years, up to a hundred. Such characteristic times do not correspond to the tens or hundreds of thousands of years that the astronomical theory of climate deals with. This theory involves parameters that are external to the climate system, whose variations are reliably known, and whose periodicities are nearly constant during a large part of Earth history [1-6]

2. QUATERNARY VARIABILITY

Abrupt changes conversely rely on fast responses to internal factors, which varied considerably during the past 2.6 Myr, and yielded more apparently irregular fluctuations. In this presentation, we recount the main climate variations determined from U1308 North Atlantic marine record, which yields a detailed calving history of the Northern Hemisphere ice sheets over the past 3.2 Myr [7]. The magnitude and periodicity of the ice rafted debris (detritic material transported by icebergs – IRD [8]) events observed in U1308 allow determining the timing of the occurrence of these particular abrupt climate changes, with the larger ones being named Heinrich events (HE) [9,10]).

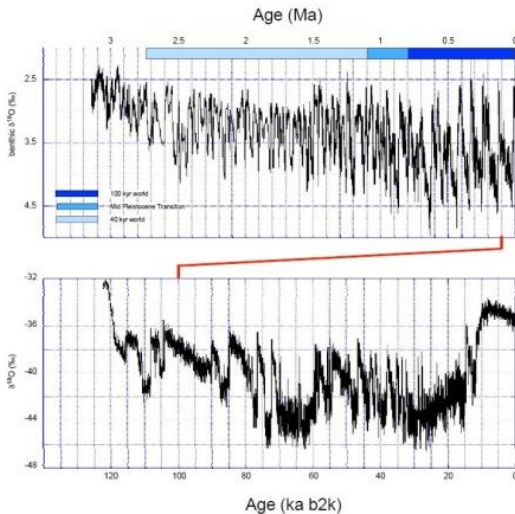


Figure 1: Proxy records of the last 3.2 Myr and 122 kyr of Earth history. Top: 3.2 Myr record Earth history from benthic $\delta^{18}O$ of the U1308 marine core [7] with indication of the 40 kyr, 100 kyr and Mid-Pleistocene transition intervals, and Bottom: 122 kyr b2k record of the $\delta^{18}O$ of the NGRIP ice core [11]. b2k: before A.D. 2000.

The North Atlantic core U1308 is representative of the main climate variations occurring during the past 3.2 Myr. The variation in the benthic $\delta^{18}O$ of this marine record in Fig. 2 clearly shows an orbitally driven

pacing with a 40-kyr periodicity in the early-to-mid record, while the last 0.65 Myr show a new pacing of about 100 kyr. The IRD record, expressed by the $\delta^{18}\text{O}$ of bulk carbonate, indicates several key changes. At 2.75 Myr b2k, the first occurrence of IRD is recorded in the North Atlantic. This corresponds to the evidence of coastal glaciers and little ice sheets in the Northern Hemisphere, mainly over Greenland and Fennoscandia, which could have calved into the ocean under appropriate environmental conditions. At 1.5 Myr b2k and onward, the delivery of icebergs to the North Atlantic increases and becomes persistent during the glacial intervals.

It is after this key date of 1.5 Myr b2k that the pacing of the major climate changes evolved from the 40-kyr cycle world to the 100-kyr cycle world, during the so-called Mid-Pleistocene Transition [12], between 1.2 Myr b2k and 0.8 Myr b2k. At 0.9 Myr b2k, the global ice volume increase is mostly concentrated in the Northern Hemisphere, with the Laurentide and the British Isles– Fennoscandian ice sheets expanding southward, inland and out over the continental shelves. The same date of 1.5 Myr corresponds also to the first major expansion of the Alpine ice cap [13,14]. At 0.65 Myr the first HEs appear, which correspond to massive iceberg discharges into the Labrador Sea, mainly originating from the Laurentide ice sheet but with the Euroasian ice sheets also contributing [15].

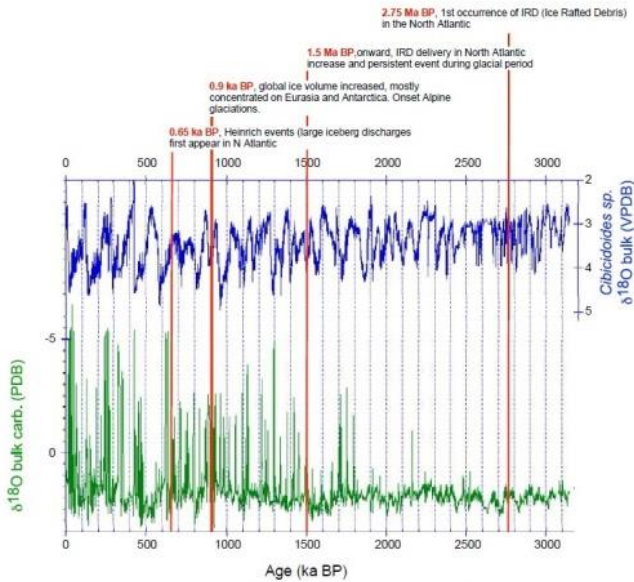


Figure 2: Variations of benthic (*Cibicidoides* sp.) $\delta^{18}\text{O}$ and of the bulk carbonates $\delta^{18}\text{O}$ (from [7]). Red vertical bars represent the five thresholds described by [7] and also determined by the recurrence analysis of these data [16].

3. THE LAST 130,000 YEAR VARIABILITY

While representative of the main climate variations occurring during the past 3.2 Myr, the $\delta^{18}\text{O}$ signal in the U1308 record of Fig. 2 only displays the classical periodicities contained in the orbital parameters. Numerous Greenland ice cores, however, have shown that other periodicities were present during the Quaternary, at least during the most recent climate cycle of the last 130,000 years [11,17,20,]. The $\delta^{18}\text{O}$ record of these ice cores also shows the occurrence of abrupt climate changes (Fig. 3) that correspond to intense warmings over the Greenland ice sheet by an average of 10-12°C [21] in about 50 years [22,23].

These intense warmings have been named Dansgaard-Oeschger (DO) events, and they correspond to warmer conditions in Europe — as indicated by pollen counts [24] and by loesspaleosols [23], and to North Atlantic Sea surface warming [10,25]. These so-called interstadial warmings lasted several hundred years [23] before the climate returned to glacial conditions, called stadials, in two main steps. The stadials were characterized by cold sea surface water in the North Atlantic [10,26], steppe-like, subtropical vegetation [27,28] and loess deposition in Europe [29,31].

Twenty-six of these stadial–interstadial cycles, also called DO cycles, have been identified [19] and they support an interpretation of these changes as resulting from internal, Earth-bound processes, as opposed to being the response to an external forcing. Moreover, the length of the interstadials appears to be related to the mean global sea level variation [32].

The long interstadials that occurred between 120 kyr and 80 kyr and between 59 kyr and 40 kyr are associated with the highest sea levels: –15 m to –45 m and –50 m to –75 m, respectively. Conversely, interstadials after 80 kyr and after 40 kyr are associated with lower sea level values, with the lowest ones, down to –125 m, having occurred during the Last Glacial Maximum (Fig. 3).

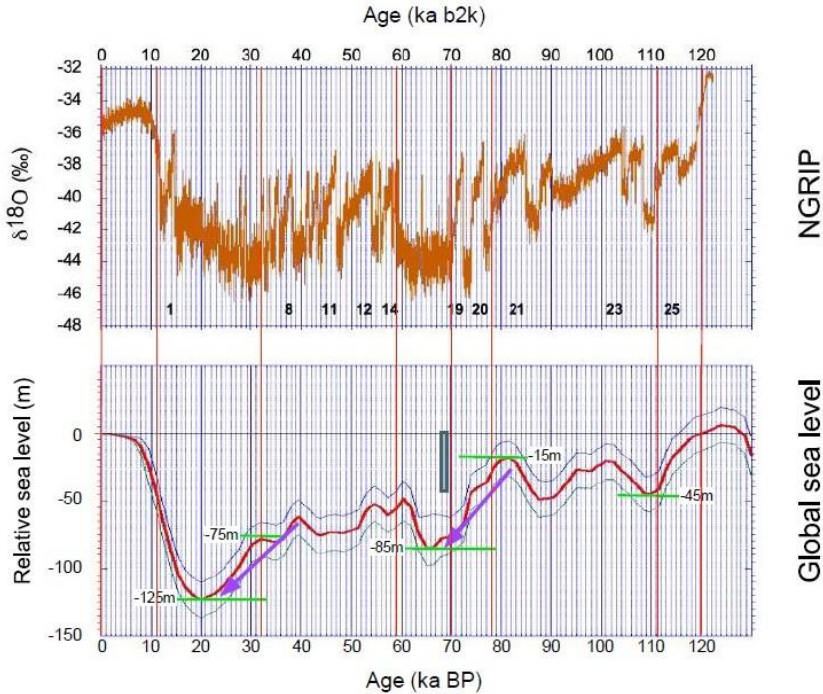


Figure 3: The last glacial cycle in NGRIP and in sea level. Top, NGRIP $\delta^{18}\text{O}$ variations over the last 122 kyr b2k [11], indicating several canonical Dansgaard-Oeschger events with the number assigned to them in [19], Bottom, variation of the sea level over the last 122 kyr BP, as reconstructed from benthic $\delta^{18}\text{O}$ foraminifera in [32]: the bold red line gives the global mean sea level (m) below present sea level, and the light blue lines are the corresponding minima and maxima. Horizontal green bars indicate several key values of sea level. Modified from [16].

Such a link between the interstadial length and sea level is expected from a simple Binge- Purge mechanism [33] with largest ice sheets expected to be easier to destabilize. Accordingly, the interval embedding the shortest DO cycles corresponds to the maximum extension of the Laurentide and Eurasian ice sheets. As DO cycles have been found also in the previous glacials down to 800 kyr [34], one can assume this pattern of climate variability has been occurring since 0.9 Myr BP, when the global ice volume increased, as indicated previously (Fig. 2).

The Greenland $\delta^{18}\text{O}$ variability has been described fairly consistently using several Northern Hemisphere records [23, 26, 35,37]. Its

comparison with the Southern Hemisphere via synchronization of the records using the CH₄ signal, a global proxy, shows an anti-phasing between the two hemispheres, with a gradual cooling in the South roughly when the North was experiencing its abrupt warmings [38,39]. A simple model has been proposed in [36] to reconstruct this “polar seesaw” in the climate variability of the two hemispheres, as represented by the δ¹⁸O records of NGRIP and the West Antarctic Ice Sheet (WAIS) Divide, respectively, over the last 60 kyr. This simple model relies on interactions between ice shelves, sea ice, the atmospheric temperature over Greenland and the North Atlantic Overturning Circulation to reproduce successfully the millennial-scale variability observed in the two hemispheres, without having to invoke the classical summer insolation curve at 65°N. [3].

4. THE BOND CYCLES

One can combine the observations of abrupt warmings — namely the DO events discussed in the previous section — with the marine IRD events, including the Heinrich events. Doing so allows one to propose a fairly simple mechanism that would generate the observed abrupt climate changes of the last 0.9 Myr.

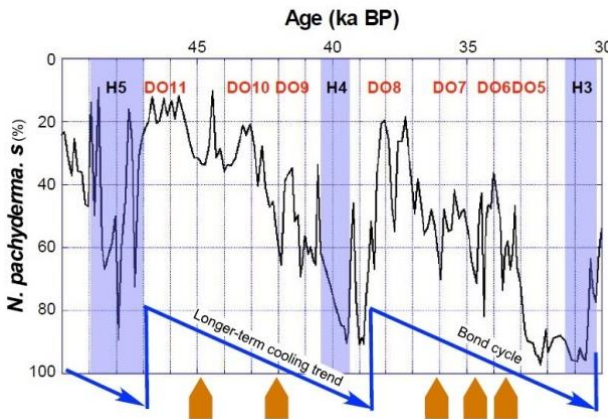


Figure 4: Amended Bond cycle mechanism. Variations in the percentage of *Neogloboquadrina pachyderma* (s.), a species indicative of cold surface water, that illustrate two Bond cycles; from DSDP 609[10].

These variations are showing a series of Dansgaard - Oeschger cycles composed of an abrupt warming (DO) and followed by a return to glacial conditions represented by "stadials". Every Bond Cycle corresponds to a long term cooling trend starting by a strong warming and ending with a stadial embedding a massive iceberg discharge into the North Atlantic (Heinrich event – H, with the assigned number by [10]). IRD events observed by [37] in contemporaneous marine records and embedded in stadials are indicated by triangles. Modified from [16].

This mechanism relies on amended Bond cycles [15], which group DO events and the associated stadials into a trend of increasing cooling intensity [37,40,41], with IRD events embedded into every stadial, the latest being an HE [16]; see Fig. 4. These Bond cycles may have occurred during the last 0.9 Myr, when Northern Hemisphere ice sheets reached their maximum extent and volume (Fig. 2), thus becoming a major player in the climate dynamics of the Late Pleistocene.

As we saw in the previous section, DO cycles and their polar seesaw can be explained entirely by intrinsic climate variability, without any external forcing [36]. The amended Bond cycle mechanism of [15], while purely descriptive, also relies essentially on processes intrinsic to the Earth system, and it does not specifically appeal to external forcing, orbital or otherwise.

To the extent that the waxing and waning of Northern Hemisphere ice sheets during Quaternary glaciation cycles is orbitally paced, it appears, though, that the abrupt climate changes observed during the Mid- and Late Pleistocene are also linked to the astronomical theory of climate, albeit rather indirectly.

5. CONCLUDING REMARKS

- Dynamical interactions between the ocean, the cryosphere with its continental ice sheets and sea ice cover, the vegetation and the atmosphere are at play in generating the millennial-scale variability that leads to abrupt climate changes. The specific triggering processes of these interactions, though, are still under discussion.
- Present investigations point to internal mechanisms being responsible for these millennial-scale events, such as periodic calving of ice sheets and intrinsic oscillations of the ice sheet–ocean–atmosphere system; see [45,42].
- Moreover, the millennial scale variability is observed from the very beginning of the last glacial cycle, and during previous glacial cycles, at least for the last 800 kyr – 900 kyr, when considering the first occurrence of Heinrich events.

- Still, we have seen that orbital forcing, as postulated by Milankovitch [1-4], sets the stage for these internal processes and modulates their period and amplitude.

Orbital-scale and millennial variabilities appear to interact during the Quaternary with millennial variability generally increasing in intensity as ice sheets grew larger in size. Thus, abrupt climate changes are definitively related, albeit indirectly, to the astronomical theory of climate.

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ORBITAL INSOLATION VARIATIONS, INTRINSIC CLIMATE VARIABILITY, AND QUATERNARY GLACIATIONS

MICHAEL GHIL

Geosciences Department and Laboratoire de Météorologie Dynamique (CNRS and IPSL), Ecole Normale Supérieure and PSL University, Paris, France, and

Department of Atmospheric and Oceanic Science, University of California at Los Angeles, Los Angeles, United States

E-mail: ghil@atmos.ucla.edu

Abstract A key question of climate variability in general, and of our planet's paleoclimatic behavior in particular, is that of the relative role of external forcing and of intrinsic variability. Over the last 100 years since Milankovitch's contributions, the role of orbital forcing has been well established for the last 2 My and their Quaternary glaciation cycles. A convincing case has also been made for the role of several internal mechanisms that are active on time scales both shorter and longer than the orbital ones and have a causal role in Dansgaard-Oeschger and Heinrich events or in the mid-Pleistocene transition, for instance. We introduce in this chapter a unified framework for the understanding of the interplay of internal mechanisms and orbital forcing on time scales from thousands to millions of years. This unified framework relies on the fairly recent theory of non-autonomous and random dynamical systems (NDSs and RDSs) and it has been successfully applied so far in the climate sciences for problems like the El Niño–Southern Oscillation, the oceans' wind-driven circulation, and other problems on interannual to interdecadal time scales. Here, we present some preliminary results of interest for the Quaternary glaciation cycles.

Key words: Bifurcations, Combination tones, Complex and nonlinear systems, Climate modeling hierarchy, Oscillations, Tipping points.

1. INTRODUCTION AND MOTIVATION

For two centuries or more of modern geology, records of our planet's physical and biological past were merely discrete sequences of strata with specific properties, like coloration and composition [40]. This state of affairs led, after initial success of the Milankovitch [48] theory of the ice

ages, to severe criticism of the mismatch between insolation minima and glaciation maxima [e.g., 19].

The advent of marine-sediment cores after World War II led, for the first time, to the availability of records that were, more or less, continuous in time. Like all climate records, these cores covered limited time intervals and did so with limited resolution and with inaccuracies in both absolute dating and the quantities being measured. Moreover, they posed the problem of inverting proxy records of isotopic and microbiotic counts to physical quantities like temperature and precipitation. In spite of these limitations, the spectral analysis of deep-sea records allowed Hays et al. [34] to overcome the difficulties previously encountered by the orbital theory of Quaternary glaciations, in particular the absence of the imprint of precessional and obliquity peaks. Specifically, Hays et al. [34] were able to create a composite record—back to over 400 ka b2k, i.e., over 400 000 yr before the present—from two relatively long marine-sediment records of the best quality available in the early 1970s.

The authors demonstrated therewith that precessional and obliquity peaks near 20 ky and 40 ky were present in this record’s spectral analysis; see Fig. 1. The power spectrum in the figure also made it quite clear that these peaks were superimposed on a continuous background — the stippled area in the figure — whose total variance much exceeded the sum of the variances present in the peaks.

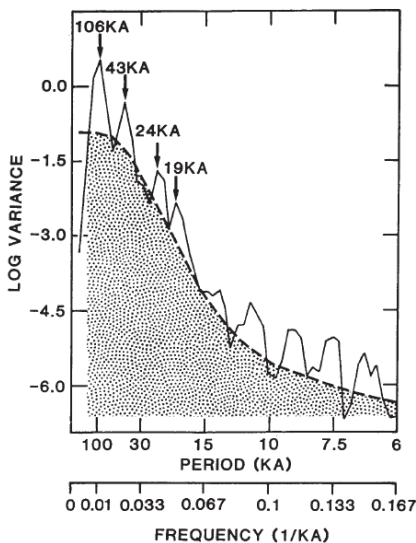


Figure 1: Power spectrum of a patched $\delta^{18}\text{O}$ record based on deep-sea cores RC11-120 and E49-18. This power spectrum is based on the work of Hays et al. [34], as presented by [40]. From Ghil and Childress [26] with permission from Springer Science+ Business Media.

The work of Hays et al. [34] and of the subsequent CLIMAP and SPECMAP projects resulted in a much more detailed spatio-temporal mapping of the Quaternary and extended the belief in the pacemaking role of orbital variations into the more remote past. At the same time, the advent of higher-resolution marine cores and, especially, ice cores from both Greenland and Antarctica, led to the discovery of Heinrich events [35], Dansgaard-Oeschger (D-O) events [e.g., 14] and Bond cycles [7] that were hard to explain by orbital forcing, given their shorter time scales. In fact, interest in past climates was heightened not only by these striking observational discoveries, but also by the growing concerns about humanity’s impact on the climate [61]. Given the declining temperatures between the 1940s and 1970s - on the one hand, as shown in Fig. 2 - and the substantial advances in the description of the Quaternary glaciations, on the other, that interest was mainly in the planet’s falling into another ice age [e.g., 49].

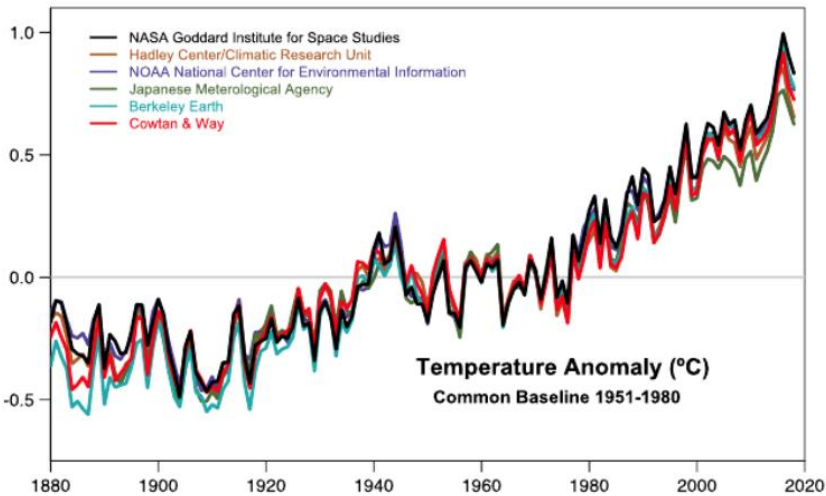


Figure 2: Comparison of six analyses of the annually and globally averaged surface temperature anomalies through 2018. In the legend, NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration. Reproduced from Lenssen et al. [45, Fig. 1] with permission from Wiley.

As a result of the double stimulation by data about glaciations and concern about them, a number of researchers in the early-to-mid 1970s worked on energy balance models (EBMs) of climate with multiple stable steady

states [20, 37, 50]. Two such stable “equilibria” corresponded to the present climate and to a “deep-freeze,” as it was called at the time, i.e., to a totally ice-covered Earth. At the time there was some disbelief about this second climate, as its temperatures were much lower than those associated with the Quaternary glaciations and incompatible with existing paleoclimatic evidence at the time.

New geochemical evidence, though, led in the early 1990s to the discovery of a snowball or, at least, slushball Earth prior to the emergence of multicellular life, sometime before 650 Ma b2k [38]. It thus turned out that this climate state — predicted by several EBMs, and confirmed by a much more detailed general circulation model (GCM; Wetherald and Manabe [66]) - had actually occurred and is now being modeled in much greater detail [28]. On the other hand, it also became clear that a model whose only stable solutions were stationary, could not reproduce very well the wealth of variability that the proxy records were describing.

Certain theoretical paleoclimatologists turned, therefore, to coupling a “climate” equation, with temperature as its only dependent variable, to an ice-sheet equation [27, 41] or a carbon-dioxide equation [56, 58].

These coupled climate models, albeit very highly idealized, did produce oscillatory solutions that captured some of the features of the Quaternary glaciation cycles as known at that time. For instance, the models of Ghil and associates [27, 41] captured the phase differences between peak ice sheet extent and minimum temperatures suggested by Ruddiman and McIntyre [55] in the North Atlantic, while the work of Saltzman and associates [e.g., 56] captured the asymmetry of the glaciation cycles with their more rapid “terminations” [8].

These oscillatory models with stable self-sustained oscillations in the presence of time-independent forcing, though, did not capture the wealth of spectral features, with their orbital and other peaks, of paleorecords available by the 1980s. The basic quandary of the Quaternary glaciation cycles - at least from the point of view of theoretical climate dynamics [26, Part IV] - is formulated in Figure 3 below; see also Ghil [22].

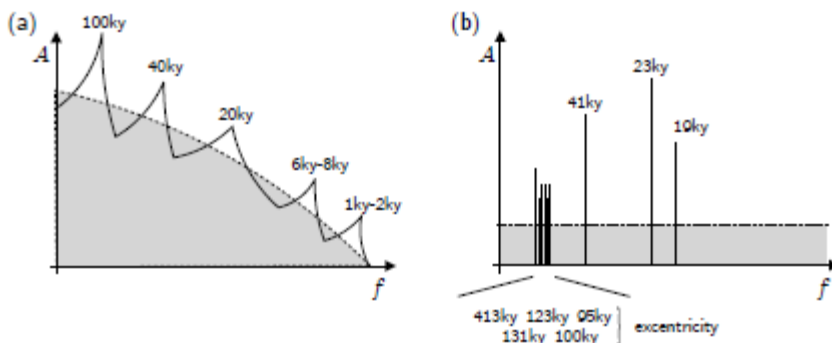


Figure 3: The theoretical quandary of modeling the Quaternary glaciation cycles, illustrated here by schematic diagrams of the composite power spectra of (a) the paleorecords and (b) the orbital forcing. In panel (a), the dominant peak for the Late Pleistocene is near 100 ky, while eccentricity forcing is distributed over several spectral lines, while the peaks at 6–8 ky and 1–2 ky correspond to recurrence of Heinrich and of D-O episodes that are not apparent in panel (b). Courtesy of N. Boers.

Based on the discussion so far and on the discrepancy between panels (a) and (b) of Fig. 3, we propose herein the following questions that need to be resolved, still, for a thorough understanding of Quaternary climate variability:

1. How does the dominant peak of the observed variability near 100 ky arise, given the rather diffuse orbital forcing around this periodicity?
2. What causes the continuous part of the observed spectrum, which contains most of the variance?
3. What gives rise to the high-frequency peaks due to the sudden warmings and to the approximate periodicities associated with the recurrence of Heinrich and D-O events, among others?
4. What are the contributions of the orbital forcing and of the climate system's intrinsic variability to items (1)–(3) and how exactly do the two interact?

In this chapter, we try to show a path toward resolving these four issues. In the next section, we summarize existing results on how the climate system's intrinsic variability arises at Quaternary time scales and on how this variability interacts with the time-dependent orbital forcing. In section 3, we outline a more general framework for the study of such interactions, as given by the theory of nonautonomous and random dynamical systems

(NDSs and RDSs), and sketch an application of this theory to other climate problems. An application to the problem at hand is proposed in Sec. 4 and conclusions follow in Sec. 5.

2. SELF-SUSTAINED CLIMATE OSCILLATORS

2.1 A Simple Mechanism for Climate Oscillations

We follow Ghil [22] in sketching the simplest physical mechanism for a self-sustained climate oscillation at fixed insolation forcing. Consider the basic workings of the Källén et al. [41] oscillator, the first such self-sustained climate oscillator, to the best of our knowledge. These workings can be represented by two coupled ordinary differential equations (ODEs), written symbolically as

$$dT/dt \simeq -V \tag{1a}$$

$$dV/dt \simeq T \tag{1b}$$

Here T stands for global temperature and V for global ice volume, while Eq. (1a) is an EBM and Eq. (1b) is an ice-sheet model (ISM). The approximate equality symbol stands for a binary relation of rough proportionality and is intended to neglect the details of the equation's right-hand side (RHS). The EBM represents the well-known ice–albedo feedback used by both Budyko [9] and Sellers [60], while the ISM relies on the precipitation – temperature feedback postulated by Källén et al. [41] and used also by Ghil and Le Treut [27], who coined the term.

The latter feedback can be better understood by writing

$$dV/dt \simeq p \tag{2a}$$

$$p = p_{ac} - p_{ab} \tag{2b}$$

$$p_{ac} \simeq T \tag{2c}$$

Here p is net precipitation on the single ice sheet of the globally integrated model, given by the difference in Eq. (2b) between the accumulation p_{ac} and the ablation p_{ab} [41].

As first observed by George C. Simpson — the meteorologist of Robert F. Scott’s Terra Nova expedition to the Antarctica in 1910–1912 and later the longest serving Director of the U.K. Meteorological Office — warmer winters have more snow and hence, at least in central Antarctica, the increase of p_{ac} with T exceeds the more obvious increase of p_{ab} with T . Hence $p \approx T$ and we have derived therewith Eq. (1b), $dV/dT \approx p \approx T$. For more recent studies of the precipitation–temperature feedback, see Tziperman and Gildor [62].

More generally, the presence of feedbacks of opposite sign in a system of two linear coupled ODEs

$$\dot{x} = y, \qquad \dot{y} = -x,$$

leads to an oscillation, with the solution given by trigonometric functions in quadrature with each other, $x(t) = \sin(t)$, $y(t) = \cos(t) = \sin(t + \pi/2)$, and the trajectory describing a circle in the (x, y) phase plane, $x^2(t) + y^2(t) = 1$. In a nonlinear system, however — like the Källén et al. [41] model or any other climate oscillator mentioned so far — the potentiality of an oscillation, as indicated by the system (1), is actually realized in the explicit, full set of equations only for certain parameter values and not for others. The simplest way to see this is by considering the so-called normal form of a Hopf bifurcation, which leads from a stable steady state, called a fixed point in dynamical systems theory, to a stable oscillatory solution, called a limit cycle. The easiest way to see this transition is by writing the normal form in polar coordinates, as in Ghil and Childress [26, Sec. 12.2], namely,

$$\dot{z} = (\mu + i\nu)z + c(zz^*)z. \tag{3}$$

Here $z = x + iy$ is complex, with $i = \sqrt{-1}$ the imaginary unit, while μ is a real bifurcation parameter, and c, ω are real and nonzero. In the [41] model, $\mu = c_T / (k c_L)$ is the ratio of the oceans’ heat capacity c_T to the characteristic time c_L of the ice sheet evolution, and k scales the outgoing longwave radiation in the full EBM that is associated with the highly simplified Eq. (1a).

A very natural transformation of variables,

$$\rho = zz^* > 0, z = \rho^{1/2} \exp(i\theta) \quad (4)$$

$$\dot{\rho} = 2\rho (\mu + c\rho) \quad (5a)$$

$$\dot{\theta} = \omega \quad (5b)$$

leads from the complex ODE (3) to the system of two real and decoupled ODEs,

Equation (5b) simply provides an angular rotation around the origin $\rho = 0 = x = y$, since the complex exponential in Eq. (4) is periodic with period 2π . Equation (5a) is quadratic in ρ and thus it can have two real roots, $\rho = \rho_0 = 0$ and $\rho = \rho_* = -\mu/c$. But ρ has to be positive and so, in the case in which $c < 0$, the only possible solution for $\mu < 0$ is the origin, and it is stable, since $\rho (\mu + c\rho)$ is negative, too, in this case; hence, ρ has to be monotonically decreasing, i.e., all the solutions of Eq. (5) spiral into the origin. The bifurcation from this stable steady state to a periodic solution with radius $\rho = \rho_*$ occurs as μ crosses 0, and this solution is stable, since now $\rho (\mu + c\rho) > 0$ for $0 < \mu < \rho_*$ and $\rho (\mu + c\rho) < 0$ for $\mu > \rho_*$, i.e. solutions will spiral out from inside the limit cycle and into it from the outside; see Ghil and Childress [26, Fig. 12.7] for the so-called supercritical, or soft bifurcation case with $c < 0$.

2.2 Intrinsic Climate Oscillations and the Mid-Pleistocene Transition

In this subsection, we present an argument for the role of intrinsic oscillations in the mid-Pleistocene transition (MPT). The argument starts with a further analysis of the Hopf bifurcation presented in the previous subsection. Such an analysis was carried out for the Källén et al. [41] model by Ghil and Tavantzis [29]. Physically speaking, the presence or absence of the regular, purely periodic oscillations obtained by Källén et al. [41] and illustrated in Ghil and Childress [26, Fig. 12.6] depends on whether $c \geq 0$.

Large μ corresponds physically to a very small, possibly pre-Pleistocene ice cap [20, 55]. At these values of μ , the Källén et al. [41] model's isoclines and fixed points — the latter being given by the intersection of the former — are very different from those that are obtained for

Quaternary-size ice sheets, for which c_L is comparable in value to c_T ; see Ghil and Tavantzis [29, Figs. 3–5]. As μ decreases to 0 (1), i.e., as we proceed from very small to more substantial ice sheets, the fixed point transfers its stability to a branch of periodic solutions, by a subcritical, or hard Hopf bifurcation [29, 39]; see also Ghil and Childress [26, Figs. 12.8 and 12.9].

For purely mechanical oscillations of a mass on a nonlinear spring with a dashpot [42], the supercritical case corresponds to a soft, sublinear spring in which the oscillations in the position x of the mass m increase gradually in amplitude as the spring constant k increases past a critical value k_* ; here the elastic force in the spring is kx^α , with $\alpha < 1$. The subcritical case corresponds to a hard, superlinear spring, where $\alpha > 1$ and the oscillations in x jump suddenly from zero amplitude to a finite amplitude as the spring constant k crosses the value k_* .

There is a clear-cut analogy in the case of the mid-Pleistocene transition, occurring at roughly 0.8 Ma, at which small-amplitude climate variability with a dominant periodicity near 40 ky becomes larger and dominated by near-100-ky periodicity [e.g. 39]. A fair number of distinct theories for this transition have been formulated [e.g. 2, 15]. A rather obvious one is that a Hopf bifurcation occurs at that point, which leads to a more vigorous response to the orbital forcing; thus, the latter does not need to change in the least in order to explain the observed phenomena. In Saltzman and Sutera [57], there is only a comment on the likely role of a Hopf bifurcation in the transition, but their Fig. 3 suggests that, in their model, such a bifurcation would have to be of the supercritical type, and lead to a fairly gradual transition. To the contrary, the subcritical Hopf bifurcation of the Källén et al. [41] and Ghil and Le Treut [27] oscillators would have to lead to a more abrupt transition, as suggested by Ghil [20]. The existing $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records might not have sufficient resolution up to 1.2 Ma to settle this question about the abruptness of the transition. In case some of them do, an objective test of suddenness, as proposed by Bagniewski et al. [4] for the high-resolution NGRIP record [1], will have to be applied to such records.

3. TIME-DEPENDENT FORCING, NDSS AND RDSS

3.1 Orbital Forcing of a Climate Oscillator

We start this section by describing some fairly simple ways in which the orbital forcing might have interacted with intrinsic climate variability, thus helping to solve the mismatch between Fig. 3(a) and 3(b). To explore this possibility, Le Treut and Ghil [43] used somewhat simplified insolation forcing, based on the calculations of Berger [5], and applied it to a slightly modified version of the Ghil and Le Treut [27] oscillator. These authors found that, as expected for a nonlinear oscillator, its internal frequency f_0 interacted with the forcing ones, $\{f_1, \dots, f_5\}$, to produce both nonlinear resonance and combination tones [42].

Depending on parameter values, the periodicity $P_0 = 1/f_0$ of the Ghil and Le Treut [27] oscillator is $P_0 \sim 6\text{--}7$ ky. The lines in the simplified insolation spectrum used by Le Treut and Ghil [43] had the periodicities

$P_1 = 19$ ky, $P_2 = 23$ ky, $P_3 = 41$ ky, $P_4 = 100$ ky, and $P_5 = 400$ ky;

these periodicities correspond to the two precessional ones, the obliquity one, and two eccentricity ones. The actual celestial mechanics calculations that Berger [5] based his insolation calculations on have been substantially updated since [e.g., 18, 63]. But these advances have not modified much the spectrum of the planetary solutions over as short an interval, in celestial-mechanics terms, as the 2 My of the Quaternary.

The results of the Le Treut and Ghil [43] model have been expressed in terms of simulated isotopic records by Le Treut et al. [44] and the spectra of the latter are plotted in Fig. 4. The values on the abscissa of Fig. 4(a) are values of the logarithm of frequency. Likewise, the values on the ordinate of both panels are powers of 10. One refers to such figures as being in (a) log–log coordinates vs. (b) log–linear coordinates for short. Aside from the spectral features noted in the figure caption and discussed in greater detail by Ghil [22], it is important to realize (i) that the large continuous background in Fig. 4(a) is purely of deterministically chaotic origin, since there is no stochastic element whatsoever in the Le Treut and Ghil [43] model or in its forcing; and (ii) that the dominant peak at 109 ky is not directly forced by the $f_4 = 1/100$ (ky) $^{-1}$ eccentricity line but rather it is due to the difference tone between the two precessional frequencies, f_1

and f_2 . Finally, it is the nonlinear, broad resonance of the model's f_0 frequency with the quasi-periodic forcing that produces the bump in the spectrum of Fig. 4(a) to the right of the orbital frequencies.

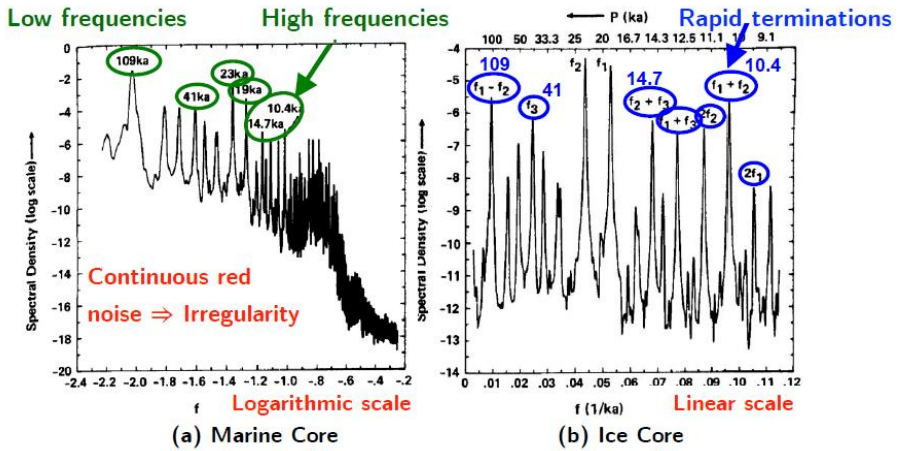


Figure 4: Power spectra of simulated (a) deep-sea and (b) ice cores for the forced climate oscillator of Le Treut and Ghil [43] with idealized orbital forcing. Panel (a) is in log–log coordinates and clearly shows a dominant peak at 109 ky and a very large amount of variance in the continuous spectrum, which has a roughly -2 power law slope. The orbital peaks at $P_1 = 19$ ky, $P_2 = 23$ ky and $P_3 = 41$ ky are also present along with peaks at 14.7 ky and 10.4 ky, which correspond to the sum tones $f_2 + f_3$ and $f_1 + f_2$, respectively. Panel (b) is in log–linear coordinates and shows additional harmonics and sum tones, as well as the difference tone $f_1 - f_2$, which corresponds to the dominant peak at 109 ky. After Le Treut et al. [44] with permission from Wiley.

3.2 Basic Facts of NDS and RDS Life

The highly preliminary results on interaction between external forcing and internal variability summarized in Sec. 3.1 encourage us to pursue in a more systematic way the interaction between orbital forcing and intrinsic climatic variability that may have contributed to generate the rich spectrum of paleoclimate on Quaternary and longer time scales [e.g., 65]. In fact, several research groups in the climate sciences have carried out during the past two decades an important extension of the dynamical-systems and model hierarchy framework presented by Ghil [23] and Ghil and Childress [26], from deterministically autonomous to nonautonomous and random dynamical systems [NDSs and RDSs: e.g., 6, 11, 32].

On the road to including deterministically time-dependent, as well as random effects, one needs to realize first that the climate system — as well as any of its subsystems, and on any time scale — is not closed: it exchanges energy, mass and momentum with its surroundings, whether other subsystems or the interplanetary space and the solid earth. The typical applications of dynamical systems theory to climate variability until not so long ago have only taken into account exchanges that are constant in time, thus keeping the model — whether governed by ordinary, partial or other differential equations — autonomous; i.e., the models had coefficients and forcings that were constant in time. Alternatively, the external forcing or the parameters were assumed to change either much more slowly than a model’s internal variability, so that the changes could be assumed to be quasi-adiabatic, or much faster, so that they could be approximated by stochastic processes. Some of these issues are covered in much greater detail by Ghil and Lucarini [28, Sec. III.G]. The key concepts and tools of NDSs and RDSs go beyond such approaches that rely in an essential way on a scale separation that is rarely, if ever, actually present in the climate sciences. The presentation herein of these key concepts and tools is aimed at as large a readership as possible and it follows Ghil [24].

Succinctly, one can write such an autonomous dynamical system as

$$\dot{\mathbf{X}} = \mathbf{F}(\mathbf{X}; \boldsymbol{\mu}) \tag{6}$$

where \mathbf{X} stands for any state vector or climate field, while \mathbf{F} is a smooth function of \mathbf{X} and of the parameter $\boldsymbol{\mu}$, but does not depend explicitly on time. This characteristic of being autonomous greatly facilitated the analysis of model solutions’ properties. For instance, two distinct trajectories, $\mathbf{X}_1(t)$ and $\mathbf{X}_2(t)$, of a well-behaved, smooth autonomous system cannot intersect, passing through the same point in phase space, because of the uniqueness of solutions. This property greatly helps draw the phase portrait of an autonomous system, as does the fact that we only need to consider the behavior of solutions $\mathbf{X}(t)$ as time t tends to $+\infty$. The sets of points so obtained are — possibly multiple — equilibria, periodic solutions, and chaotic sets. In the language of dynamical systems theory, these are called, respectively: fixed points, limit cycles, and strange attractors. We know only too well, however, that the seasonal cycle plays

a key role in climate variability on many time scales, while orbital forcing is crucial on the Quaternary time scales of many millennia, and now anthropogenic forcing is of utmost importance on interdecadal time scales. How can one take into account such time-dependent forcings, and analyze the nonautonomous systems, written succinctly as

$$\dot{\mathbf{X}} = \mathbf{F}(\mathbf{X}, t; \mu) \tag{7}$$

to which they give rise? In Eq. (7), the dependence of \mathbf{F} on t may be periodic, $\mathbf{F}(\mathbf{X}, t + P) = \mathbf{F}(\mathbf{X}, t)$, as in various El Niño–Southern Oscillation (ENSO) models, where the period $P = 12$ months, or monotone, $\mathbf{F}(\mathbf{X}, t + \tau) \geq \mathbf{F}(\mathbf{X}, t)$, as in studying scenarios of anthropogenic climate forcing. An even more general situation includes time dependence in one or more parameters $\{\mu_1, \dots, \mu_P\}$.

To illustrate the fundamental distinction between an autonomous system like Eq. (6) and a nonautonomous one like Eq. (7), consider the simple scalar version of these two equations:

$$\dot{X} = -\beta X, \quad \text{and} \tag{8a}$$

$$\dot{X} = -\beta X + \gamma t, \tag{8b}$$

respectively. We assume that both systems are dissipative, i.e. $\beta > 0$, and that the forcing is monotone increasing, $\beta \geq 0$, as would be the case for anthropogenic forcing in the industrial era. Lorenz [46] pointed out the key role of dissipativity in giving rise to strange, but attracting solution behavior, while Ghil and Childress [26] emphasized its importance and pervasive character in climate dynamics. Clearly the only attractor for the solutions of Eq. (8a), given any initial point $X(0) = X_0$, is the fixed point $X = 0$, attained as $t \rightarrow +\infty$.

In the case of Eq. (8b), though, this forward-in-time approach yields blow-up as $t \rightarrow +\infty$, for any initial point. To make sense of what happens in the case of time-dependent forcing, one introduces instead the pullback approach, in which solutions are allowed to still depend on the time t at which we observe them, but also on a time s from which the solution is started, with $X(s) = X_0$ and $s \ll t$. With this little change of approach, one can easily verify that

$$|X(s, t; X_0) - A(t)| \rightarrow 0 \text{ as } s \rightarrow -\infty, \quad (9)$$

for all t and X_0 , where $A(t) = (\gamma/\beta) (t - 1/\beta)$. We thus obtain, in this pullback sense, the intuitively obvious result that the solutions, if we start them far enough in the past, all approach the attractor set $A(t)$, which has a linear growth in time, thus following the forcing.

Let us return now to the more general, nonlinear case of Eq. (7) and add not only deterministic time dependence $\mathbf{F}(\mathbf{X}, t)$, but also random forcing,

$$d\mathbf{X} = \mathbf{F}(\mathbf{X}, t) dt + \mathbf{G}(\mathbf{X}) d\eta, \quad (10)$$

where $\eta = \eta(t, \omega)$ represents a Wiener process — with $d\eta$ commonly referred to as “white noise” — and ω labels the particular realization of this random process. When $\mathbf{G} = \text{const.}$ the noise is additive, while for $\partial\mathbf{G} / \partial\mathbf{X} \neq 0$ we speak of multiplicative noise. The distinction between dt and $d\eta$ in the stochastic differential equation (10) is necessary since, roughly speaking and following the Einstein [17] paper on Brownian motion, it is the variance of a Wiener process that is proportional to time and thus $d\eta \propto (dt)^{1/2}$.

The noise processes may include “weather” and volcanic eruptions when $\mathbf{X}(t)$ is “climate,” thus generalizing the linear model of Hasselmann [31], or cloud processes when we are dealing with the weather itself: one person’s signal is another person’s noise, as the saying goes. In the case of random forcing, the concepts introduced by the simple example of Eq. (8b) above can be illustrated by the random attractor $\mathcal{A}(\omega)$ in Fig. 5.

Chekroun et al. [11] studied a specific case of such a random attractor for the paradigmatic, climate-related Lorenz [46] convection model. The authors introduced multiplicative noise into each of the ODEs of the original, deterministically chaotic system, as shown below:

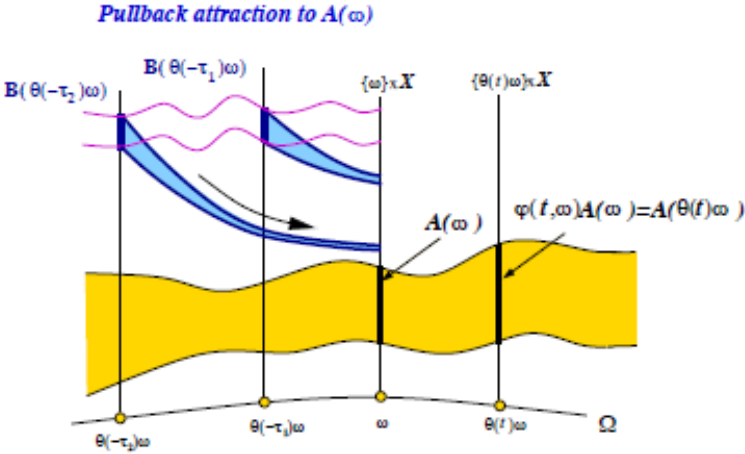


Figure 5: Schematic diagram of a random attractor $\mathcal{A}(\omega)$ and of the pullback attraction to it; here ω labels the particular realization of the random process $\theta(t, \omega)$ that drives the system. We illustrate the evolution in time t of the random process $\theta(t, \omega)$ (light solid black line at the bottom); the random attractor $\mathcal{A}(\omega)$ itself (yellow band in the middle), with the snapshots $\mathcal{A}(\omega) = \mathcal{A}(\omega; t=0)$ and $\mathcal{A}(\omega; t)$ (the two vertical sections, heavy solid); and the flow of an arbitrary compact set \mathcal{B} from “pullback times” $t = -\tau_2$ and $t = -\tau_1$ onto the attractor (heavy blue arrows). Reproduced from Ghil et al. [32] with permission from Elsevier.

$$dX = P_r (Y - X) dt + \sigma X d\eta, \tag{11a}$$

$$dY = (rX - Y - XZ) dt + \sigma Y d\eta, \tag{11b}$$

$$dZ = (-bZ + XY) dt + \sigma Z d\eta; \tag{11c}$$

here $r = 28$, $P_r = 10$, $b = 8/3$ are the standard parameter values for chaotic behavior in the absence of noise, and σ is a constant variance that is not necessarily small. The well-known strange attractor of the deterministic case is replaced by the Lorenz model’s random attractor, dubbed LORA by the authors. Four snapshots of LORA are plotted in Fig. 6 and a video of its evolution in time is available as Supplementary Material in [11] at <https://doi.org/10.1016/j.physd.2011.06.005>. Charó et al. [10] have further analyzed the striking effects of the noise on the nonlinear dynamics that are visible in Fig. 6 here and in the video of [11], and gathered further insights into the abrupt changes of the snapshots’ topology. These remarkable changes suggest the possibility of random

processes making important contributions to jumps in paleoclimatic variability, such as the MPT.

4. AN RDS FOR THE QUATERNARY GLACIATIONS

Apparently, it is Crucifix [13] who first applied pullback ideas to the problems of Quaternary glaciations, independently of earlier work on the topic in the climate literature [6, 11, 32]. His work concentrated mainly on the connection between the pacemaking role of the orbital forcing and the observed irregularity of the glacial terminations during the late Pleistocene, cf. Broecker and Van Donk [8] and Ghil and Childress [26, Fig. 11.2].

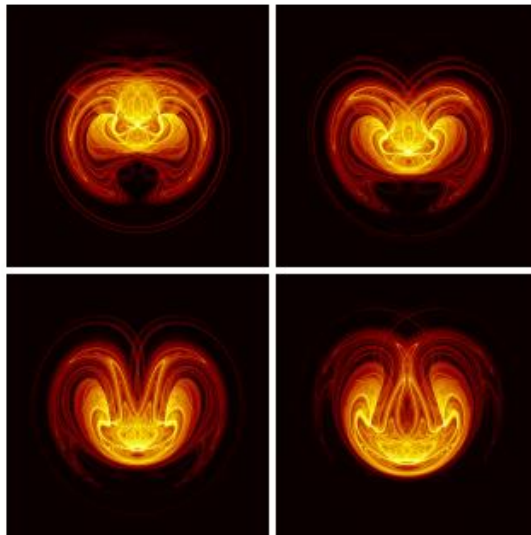


Figure 6: Four snapshots of LORA and the invariant measure $\nu(\omega)$ supported on it. The values of the parameters r , P_r and b are the classical ones, while $\sigma = 0.5$. The color bar is on a log-scale and it quantifies the probability of landing in a particular region of phase space; shown is a projection of the 3D phase space (X,Y,Z) onto the (X,Z) plane. Note the complex, interlaced filament structures between highly populated regions (in yellow) and moderately populated ones (in red). Reproduced from Ghil et al. [32] with permission from Elsevier.

Based on the considerable success of NDS and RDS applications to other climate problems — such as ENSO [12, 31, 32, 47], the wind-driven ocean circulation [51, 52] or the evaluation of the ensemble simulations routinely performed in support of the Assessment Reports of the

Intergovernmental Panel on Climate Change [16, 64] — it would appear worthwhile to proceed further along these lines.

The concepts and tools summarized in Sec. 3.2 could shed further light on several problems not quite yet solved concerning Quaternary glaciations and paleoclimate in general. A short and highly incomplete list of the interesting problems that might gain by such a treatment is the following:

1. What are the causes of the MPT and what is the part of intrinsic climate variability and that of the orbital forcing therein? See discussion in Sec. 2.2.
2. What causes the large continuous background of the observed spectrum: is it deterministic chaos, stochastic forcing or both? See discussion of Fig. 4.
3. Particularly complex problems are associated not only with the causes of Heinrich and D-O events, but with their modulation over longer time intervals by orbital forcing and other slow-acting changes in atmospheric composition, geology, ocean circulation, and so on. See, for instance, [54, and references therein].
4. While the occurrence of a snowball mode several times in Earth's geologic history is well established by now, we still know relatively little about how the planet got into, and especially out of, such a mode [e.g., 53].

Of course, each of these problems requires one or more distinct climate models, as well as very careful modeling of the kinds of time-dependent changes in forcing and parameters that are most enlightening, as well as most relevant and plausible. A good way would be to start testing ideas with relatively simple models and pursue the investigation systematically across a hierarchy of models — through intermediate ones and on to the most detailed ones — in order to further increase understanding of the climate system and of its predictability on the various paleoclimatic time scales mentioned in the list above. Such an approach can usefully complement the more common one of merely pushing onwards to higher and higher model resolution in order to achieve ever more detailed simulations of the system's behavior for a limited set of semi-empirical parameter values. Ghil [23] and Held [36], among others, have

emphasized the need to pursue such a model hierarchy, as originally proposed by [59], in order to balance the need to broaden the number of plausible hypotheses vs the need for confronting them with spatio-temporal details derived from observations.

5. CONCLUDING REMARKS

In this review, we have covered in Sec. 1 the contributions of the 1970s to the rebirth of the Milankovitch [48] theory of the ice ages and in Sec. 2 the 1980s advances in modeling the Quaternary climate's intrinsic variability. In Sec. 3, we presented first results on the interaction between the orbital insolation forcing of Sec. 1 and the intrinsic variability of Sec. 2, and proceeded to introduce the novel concepts and tools of the theory of nonautonomous and random dynamical systems (NDSs and RDSs) that can help to better model and understand this interaction. Finally, in Sec. 4, we listed a number of open issues on Quaternary and longer paleoclimate time scales, and proposed to address them by the tools of Sec. 3.2.

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WLADIMIR KÖPPEN, ALFRED WEGENER, AND MILUTIN MILANKOVITCH: THEIR IMPACT ON MODERN PALEOCLIMATE RESEARCH AND THE REVIVAL OF THE MILANKOVITCH HYPOTHESIS

JÖRN THIEDE

St. Petersburg State University, 7–9, Universitetskaya nab., St. Petersburg, 199034, Russian Federation

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Wladimir Köppen (1846–1940, originally from St. Petersburg), Alfred Wegener (1880–1930, originally from Berlin) and Milutin Milankovitch (1879–1958, originally from Dalj, then Austria-Hungary, today eastern Croatia) made significant contributions to paleoclimatology during the early years of the 20th century. Köppen described the global climate zonation, Wegener defined the continental drift during the Phanerozoic, using Köppen climate zonations applied to paleogeographic scenarios of the geological past, and Milankovitch introduced regularly changing orbital parameters as controls of past climatic changes providing a precise timescale for Glacials and Interglacials during the Quaternary. By combining their scientific efforts, they succeeded to change our understanding of Earth history fundamentally, each of them with their specific expertise and their wide scientific horizons. Wladimir Köppen’s scientific work began with observations from the Crimea and from contributing to produce synoptic weather maps while he was working at the Central Physical Observatory in St. Petersburg. Later he pursued his scientific career at the “Deutsche Seewarte” in Hamburg. While producing numerous scientific papers, he was also engaged in instrumental development (kite technology) and in shaping the organisational framework for meteorology, both nationally and internationally. One of his major scientific achievements was the definition of the global climate zonation which he repeatedly published in global maps and which is still used today.

Keywords: Paleoclimatology, Glacials and interglacials, Milankovitch frequencies, Cyclostratigraphy, Wladimir Köppen, Alfred Wegener, Milutin Milankovitch.

INTRODUCTION

This paper has been written for the Vestnik of St. Petersburg State University, Earth Sciences to commemorate the scientific achievements of Wladimir Köppen (1846–1940), who was born in St. Petersburg, had his first scientific position at the Central Physical Observatory of St. Petersburg and developed in young years into one of the globally leading meteorologists. The new Köppen Laboratory of the Institute of Earth Sciences of SpbGU has been named in honor of him, with the aim to remind the active relevant scientific community and the young generations of meteorologists, geographers and paleoclimatologists in Russia of this important man. St. Petersburg later developed into a “Mekka” of climate and paleoclimate sciences, as can be concluded based on the results of Michael I. Budyko (1920–2001, cf. Budyko, et al., 1987) as well as the researchers who are presently working at various scientific institutions in St. Petersburg. Köppen’s 170th birthday was heralded by Khayrullin 2016 in the Proceedings of the Voeikov Main Geophysical Laboratory in St. Petersburg which developed from the Central Physical Observatory, where Köppen had his first position during his early years in St. Petersburg.

The global climate has shown great variability through the Earth’s history, but strangely enough the climate extremes never exceeded the narrow window of temperatures (both on the warm as well on the cold end), which allows life to exist, for the past 3–4 billion years (Summerhayes, 2015). The sedimentary records documenting the Earth’s history contain evidence for “glacial” events (or glacial climatic phases) of a widely different nature, ranging from “unipolar” glaciations (with huge ice sheets when one of the poles was covered by a large and high continent such as during the Permo-Carboniferous, while the other pole was located in the open ocean and kept ice-free due to the potential advection of temperate waters), the “snowball earth” situation at the end of the Precambrian (when most of our globe apparently was covered by ice) to bipolar glaciations such as during the Cenozoic. At that time, young plate tectonic movements had generated a paleogeographic situation with climatically/oceanographically isolated physiographic provinces on the

southern and northern hemispheres. Ideas about the origin of tills and occurrences of erratics (which at that time were considered very strange deposits) as indicators of glaciation, alternating obviously with sediments of a non-glacial nature, started to surface during the early 19th century (Agassiz, 1838; Esmark, 1824).

Sedimentation patterns (stratigraphies) often reveal cyclic repetitions of their properties, following cycles of a wide variety, length and causalities. Schulz et al. (1999) linked 1470-year climate oscillations (Dansgaard-Oeschger Interstadials) during the last 100,000 years to fluctuations of continental ice mass. Wang et al. (1999) explained periodicities of 84, 102 and 775 years in Holocene South China Sea records to monsoon variations caused by long-term oscillations in thermohaline circulation and solar activity cycles. Sierro et al. (2000) calibrated Atlantic climatic records to Mediterranean sapropels and astronomical oscillations. But none of these are as important as the variations between Glacials and Interglacials, which seem to follow each other in a cyclical pattern controlled by the Milankovitch frequencies (Past Interglacials Working Group..., 2016) with longer wave lengths than the examples mentioned above. The latter paper puts a focus on the question how Interglacials end, how their paleoclimate gives way to the following Glacials and the authors speculate, how the modern Interglacial's climate may change in the future. This question is of high societal relevance.

It is also of high socioeconomic relevance because our highly developed societies with their complex technologies urgently need scientifically based “early warning systems” of the imminent climatic changes and their environmental consequences which we might experience in the future. It is here, where Köppen, Wegener and Milankovitch made their biggest contribution.

WLADIMIR KÖPPEN, HIS ORIGIN AND FAMILY

Wladimir Peter (Petrovitch) Köppen (* Sept. 25, 1846 in St. Petersburg, + June 22, 1940 in Graz/Austria, at that time part of the “German Reich”) was born into a family with German roots. His grandfather, a physician (Johann Friedrich Köppen, * 1752 in Schwedt/ Oder, + 1808 in Kharkov), had been invited by Catherine the Great in 1786 to help with the medical services in the Russian Empire. In 1793 he was appointed the chief physician of the Slobodsko-Ukraine (later Kharkov) government. As a

subject of the Russian Empire he was now known by the name Ivan Ivanovich. In 1811, the family was elevated to nobility. The son Pjotr Ivanovitch Köppen (* Febr. 19, 1793 in Kharkov, + May 23, 1864 on the Crimea and father to Wladimir Köppen, who also had three brothers and three sisters) became a noted archeologist, geographer and statistician and was elected member of the (Imperial) St. Petersburg Academy of Sciences.



Figure 1: South coast of the Crimea at Karabakh (today part of the town of Alushta) where the Köppen family owned an estate/vinery

In 1829, he purchased a vinyard on the Crimea's South Coast in the village of Bijuk - Lambat, presently Malyi Mayak (in the area of Alushta), later acquired adjacent parcels of land and finally made this estate his permanent home, named "Karabakh" (Black Vinyard), after the name of the first parcel (Fig. 1). Although the estate was lost after the revolution, family graves (Fig. 2) and memories of the Köppen family (street name in Alushta) are preserved in the area even today.



Figure 2: Gravestone of the Köppen - family in Karabakh (Alushta, South coast of the Crimea) where the Köppen - family owned a vinery/estate



Figure 3: The “Academics House” in St. Petersburg in modern time. The black plaques between the windows commemorate the many famous academicians who have been living here over the years with their families, like the Köppens (Photo: S. Thiede, June 18, 2017)



Figure 4: Certificate of Wladimir Köppen's honorary doctoral degree from the University of Hamburg (dated July 14, 1926, courtesy of Dr. Gunther Schonharting, Eichhofen/Germany)

Being a member of the Imperial Russian Academy of Sciences, Pjotr von Köppen and his family were also given a flat in the “Academics House” in St. Petersburg (modern address: nab. Leitenanta Shmidta, nr. 1, Fig. 3) which became famous, also because the Russian Geographical Society was founded in this flat on August 6, 1845. Wladimir Köppen later served 1872–1874 this society as its secretary. He moved from St. Petersburg to Hamburg/Germany in 1875, later from Hamburg to Graz/Austria in 1924 (see details further below). His professional and scientific development can be deduced from his bibliography published in (Wegener and Köppen, 1955). The young Alfred Wegener got in touch with Wladimir Köppen in the early years of the 20th century because he sought his advice on a number of scientific issues (see below) and began to visit his senior colleague. During this time, Alfred Wegener fell in love with Else, one of Wladimir Köppen's daughters and the scientific liaison soon developed into close family bonds which remained throughout Köppen's life until he died in Graz in 1940.



Figure 5: *Photography of celebrities who met at the occasion of the 25th anniversary of the foundation of the “Deutsche Seewarte” on Febr. 1, 1900. G. von Neumayer — 1st left front row, beside him K. Koldewey (leader of the first German North Pole Expedition 1868), Wladimir Köppen (approx. 50 years old) during his active years 2nd from the right (Source: Archive of the “Deutsche Seewarte”, today BSH in Hamburg)*

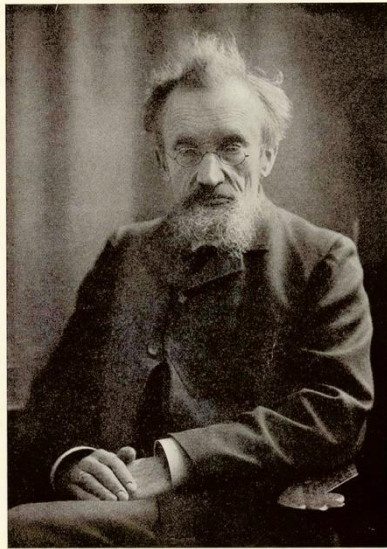


Figure 6: Wladimir Köppen as an elderly man (courtesy of director of archive of the St. Petersburg State University Library Marina Karpova)

W. Köppen



Figure 7: Gravestone of the Köppen family in Graz/Austria (Photo: Dr. R. Krause, AWI, Bremerhaven)



Else (* Febr. 1, 1892, + Aug. 27, 1992) became the editor of Köppen's biography (Wegener and Köppen, 1955), a translation of the German text into Russian is presently being prepared and has been published by the Russian Publishing House Paulsen.ru after in Moscow in May 2018; the original German text was republished together with a translation into English by Borntraeger Science Publishers — Stuttgart during 2018).

Köppen's biography, based on his personal notes, was later published by (Wegener and Köppen, 1955). It revealed also some of his social activities which went far beyond his professional work. Beside his regular duties at his scientific home institution, after some time he also established a

relationship to the then very young University of Hamburg. He became a (titular) professor in Hamburg and he received an honorary doctoral degree in 1926 from the University of Hamburg at the occasion of his 80th birthday (Fig. 4). His main scientific accomplishments were related to global climate classifications, which were based on a mathematically defined and quantified subdivision of the major climate zones of planet Earth, which — however — are not the subject of this article.

Wladimir Köppen (Figs 5 and 6) stayed for over 40 years at the “Deutsche Seewarte” and was succeeded in 1919 by his son-in-law Alfred Wegener, who in 1924 accepted a professorship in meteorology and geophysics at the University of Graz/Austria. At that time both had established a mature scientific partnership as manifested by their jointly authored book “The Climates of the Geological Past” (Köppen and Wegener, 1924) which also brought them both into close scientific contacts with Milutin Milankovitch. Both families moved from Hamburg to Graz in 1924 and Wegener as well as Köppen continued their active scientific life until they died, Wegener (1930, only 50 years old) towards the end of his famous expeditions to the top of the Greenland ice sheet in 1929/1930, Köppen because of his age in 1940 in Graz. Wegener’s death caused much grief in the families.

Köppen’s Russian origin caused some traumatic experiences, although not much is written about this in his biography. During 1870, he finalized his studies at the universities of Heidelberg and Leipzig and became a witness to the many casualties of the German war against France. He then volunteered to serve as a medic for some time. In 1914 WW I broke out, with the Russian and German empires on opposite sides. As an employee (“Beamter, Admiralitätsrat”) of the “Deutsche Seewarte” Köppen had to be loyal to his employer. With the communist revolution, the family lost their estate in Crimea and contacts to Russia became very difficult, even though some of the wider family circle remained in Russia. Köppen died in Graz in June 1940, working up to his last days (Wegener and Köppen, 1955) on scientific publications, almost precisely 1 year before the completely unjustified attack of the “Deutsches Reich” on the Soviet Union (Figs 5–7).

The Köppen family can be considered as an excellent example for the flow of scientists between western Europe and the Russian empire who made important contributions to the evolution of academic environments in

Russia (Ludecke, 2003), but in the case of Wladimir Köppen also moving from Russia to Germany, to a western country.

KÖPPEN AND HIS IMPACT ON METEOROLOGY

Wladimir Köppen spent a lot of time on the Crimea during his young years, visiting a high school in Simferopol. He caught a substantial interest in the vegetational zonations related to the morphology (and henceforth climate, temperature, precipitation) of the mountaineous southern Crimea. He actually wrote his very first publication about temperature variations in Karabakh (Wegener and Köppen, 1955).

Wladimir Köppen began his time as a student, first devoted to botany in St. Petersburg in Sept. 1864. His impressions from the Crimea motivated him to take up studies in meteorology and related subjects and he moved to the universities of Heidelberg and Leipzig in Germany where he acquired his doctorate in 1870. He then moved back to Russia and he got his first position at the Central Physical Observatory in St. Petersburg (1872–1874) and deepened his knowledge of meteorological processes, in particular the global distribution of climatic zones.

This laboratory was under the leadership of Heinrich von Wild, a Swiss meteorologist who had moved to Russia, who had become a member of the Russian Academy of Sciences and president of the International Polar Commission. He was instrumental to organize the Russian contribution to the 1st International Polar Year (IPY, 1882–1883), with an important scientific station on the island Sagastyr in the Lena Delta. This was some years after Köppen had moved to Hamburg and there can be no doubt that he played a pivotal role in the contacts between Georg Neumayer (Director of the “Deutsche Seewarte” in Hamburg) and Heinrich von Wild, his former boss when promoting the 1st IPY.

He visited international meetings of meteorologists and soon became quite famous in Russia and abroad. He was then “discovered” by Georg Neumayer, founder and director of the “Deutsche Seewarte” in Hamburg (later the DHI = “Deutsches Hydrographisches Institut”, nowadays the BSH = “Bundesamt für Seeschifffahrt und Hydrographie”), who on March 15, 1875 offered Köppen a position as department head in applied meteorology in his new institution. Neumayer was building up the “Deutsche Seewarte” and urgently needed qualified scientists. Köppen’s

department was commissioned to gather daily weather observations needed for sailing instructions. He published articles/books on the global climate zones (Köppen, 1923; Köppen, 1936) and already in young years he became a famous and well established leading meteorologist (cf. Wegener and Köppen, 1955, for a complete listing of his publications in German).

Georg Neumayer (since 1900 Georg Ritter von Neumayer, Fig. 5) was a towering figure in climate and in particular polar related sciences in Europe. He was the promoter of the 1. International Polar Year 1882/83 which was based on the original ideas of Carl Weyprecht (1838–1881) who, however, had died a few years before. Even though Wladimir Köppen was very young at that time, he excelled scientifically and it must have been very flattering for him to be invited as a scientist to serve at a renowned foreign hydrographic institution (from 1876 to 1919). His German roots may have helped, but it was probably the congenial scientific perspectives of Neumayer and Köppen, who brought these 2 scientists to work together for many years, until Georg von Neumayer retired in 1903, to return to the Palatinate where he originally came from. It soon became clear to both of them that weather services required international collaboration. Köppen became for some time department head for Weather Services/Applied Meteorology at this new institution, but was later relieved from the many administrative duties in favor of his scientific work and stayed there until retirement in 1919 (being succeeded by his son-in-law and close friend as well as scientific collaborator Alfred Wegener).

Köppen also played an important role within the German Meteorologic Society and the foundation of the German Weather Service replacing Neumayer after retirement (Tetzlaff, et al., 2008). In Germany, Köppen soon was involved in numerous professional activities as part of his duties at the “Deutsche Seewarte” (1875–1945) of the German (then mainly Prussian) Navy, which had evolved from the “Norddeutsche Seewarte”, a private institution which had been led by Wilhelm von Freeden and which existed 1867–1875.

Details of his scientific life in Hamburg can be found in (Wegener and Köppen, 1955), his biography compiled by his daughter based on his personal notes. A laudatio with many personal aspects has been published by his colleagues at the “Deutsche Seewarte” at the occasion of his 80th

birthday in 1926 (Deutsche Seewarte Hamburg, 1926). One particular interesting technical detail is the development of kite-technology for meteorologic measurements at height which led to the establishment of the kite-station of the “Deutsche Seewarte” in Gross Borstel in the northern suburbs of Hamburg.

KÖPPEN’S COOPERATION WITH ALFRED L. WEGENER

Alfred Wegener has worked and published about a very diverse and broad range of scientific subjects, on many of them by writing quite comprehensive books. His doctoral thesis (Wegener, 1905) dealt with the Alfonsinian Tables which comprise a medieval astronomical document allowing to calculate the positions of sun, moon and the five planets, certainly a strange subject. But it probably prepared Wegener later to occupy himself with the question of the Milankovitch frequencies. He later took up a truly meteorologic theme (Wegener, 1911) which made him to establish scientific contact with Wladimir Köppen who by that time was an established and experienced meteorologist and who commented extensively on Wegener’s book about “Thermodynamik der Atmosphäre” (Deutsche Seewarte Hamburg, 1926).

During the early years of the last century the young Alfred Wegener contacted Wladimir Köppen on meteorologic questions, but also because he had the idea that the geography of planet Earth had gone through major changes. He wanted to prove through the means of reconstructions (“historic” — in a geological sense) of former climate zonations,

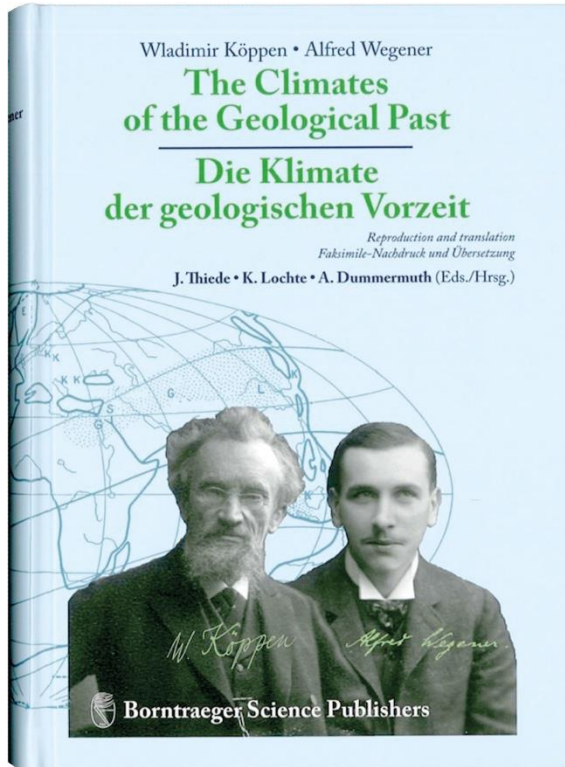


Figure 8: Cover of the famous book of Köppen & Wegener 1924, as reprinted in 2015, together with a translation into English

which he believed to be stable as related to the geometry of the earth's orbit around the sun, but contrary to the changing geographic positions of the continents.

Alfred Wegener achieved world renown with the publication of his book "The Origin of Continents and Oceans" in 1915. With four editions printed between 1915 and 1929 (see Wegener, 2005), Wegener's hypothesis on the "origin of continents and oceans" was highly controversial at that time. At first, Köppen was skeptical of Alfred Wegener's ideas about the "Origin of Oceans and Continents" (Continental Drift Hypothesis), but later (around 1919; Deutsche Seewarte Hamburg, 1926) he changed his scientific position and became an ardent defender of Wegener's ideas. The peak of their scientific relationship was reached when Wladimir Köppen and Alfred Wegener jointly published their

monograph on “Die Klimate der geologischen Vorzeit” (Climates of the Geological Past) in 1924, which has recently been republished (Fig. 8). This book contains an important monographic interpretation on the causal relationships of climate change in the geological past (Köppen and Wegener, 1924). Before his death in 1940 at the age of 93, Köppen made additions to their work under the title “Supplements and Corrections”, notifying the printing office that he “urgently needed the proofs because he was dying” (Wegener and Köppen, 1955).

Only one edition of Köppen’s & Wegener’s book of 1924 was printed and unfortunately, most copies of this edition were lost, including all originals, during World War II. Because of its importance in the light of modern climate and paleoclimate research, the Alfred-Wegener-Institute, Helmholtz Center for Polar and Marine Sciences in Bremerhaven/Germany together with the original publisher (Gebr. Borntraeger in Berlin) and with the support of a number of learned societies and research institutions in Germany decided to reprint this book (in its original form), and to furnish it with an English translation, in order to make it available to the wide modern international community of climate researchers.

Köppen’s & Wegener’s book (1924) is of principal scientific interest for several reasons: — it contains a systematic inventory and description of the sedimentological and paleontological arguments which Wegener used to establish his historic (in a geological sense) climate zones for most of the Paleozoic, Mesozoic and Cenozoic paleogeographic reconstructions. During the first two decades of the last century Köppen had developed important concepts of the modern global distributions of climate zones (see Köppen, 1923, 1936 for summaries). The close cooperation between Wegener and Köppen led to their mutual conviction that these zones could in principle also be deduced from the stratigraphic records of fossil climate indicators;

— the book critically describes and discusses paleogeographic reconstructions for most of the Phanerozoic periods. Because Köppen was fluent in Russian he was able to draw on information from many less known regions, for example, northern Eurasia;

— the book then ventures into hypothesizing about climate changes in Earth history. The most important element of this discussion stems from a close collaboration they had established with Milankovitch. He claimed and precisely calculated that the Late Cenozoic climate changes were controlled by systematic variations of some of the parameters controlling

the geometry of the earth's orbit around the sun (eccentricity, obliquity, precession) generating differences in the insolation. Milankovitch actually allowed them to use his text, calculations and figures (Fig. 9);

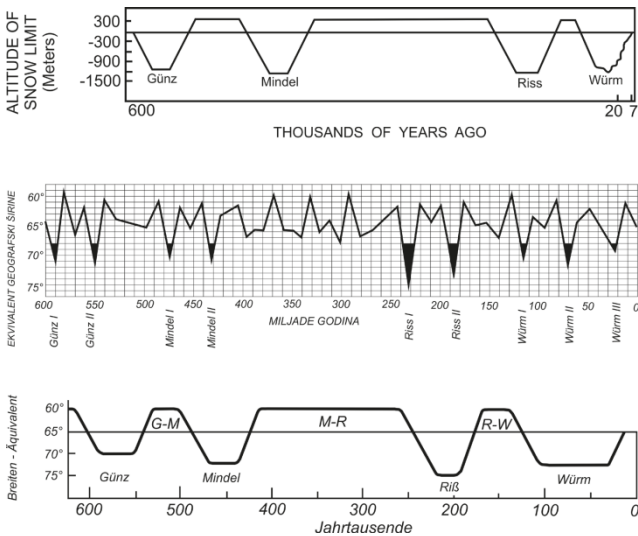


Figure 9: Inclusion of Milankovitch data into Köppen's and Wegener's considerations. Uppermost panel: Penck and Bruckner's curve showing the climate during the Pleistocene period (published 1909). Middle panel: Milankovitch's radiation curve for latitude 65° N forwarded to Köppen in 1924. Lower panel: Sequence of Late Quaternary Glacials and Interglacials (after Penck & Bruckner, 1909) adapted to their timing deduced from Milankovitch's radiation curve by drawing a horizontal line at latitude 65° N (cited from Berger, 1995)

acceptance of the principles of the Milankovitch frequencies made it possible for the first time early in the last century to establish a precisely defined time scale of Late Cenozoic glacial-interglacial history. Later it was shown that Milankovitch frequencies could not only be reconstructed from Quaternary sediments, but that they could also be found in the cyclostratigraphy of deposits from many periods of the Phanerozoic (Schwarzacher, 1993, see below).

KÖPPEN'S AND WEGENER'S COOPERATION WITH MILANKOVITCH

When writing their book (Köppen and Wegener, 1924) the authors contacted Milutin Milankovitch who was engaged in calculating the

geometric properties of the earth's orbit around the sun (eccentricity, obliquity, precession) and deducing from them regular insolation changes (mainly around a latitude of 65° N). He believed that they controlled the Late Tertiary and Quaternary alternations between Glacials and Interglacials; he actually provided figures to Köppen and Wegener (Fig. 9). His idea was by no means completely new, but originated from some British geoscientists in the early and middle 19th century (a good historic account of the developments of this thinking can be found in Summerhayes, 2015).

The scientific relationship between Milankovitch, Köppen and Wegener has been elucidated in a book edited by A. Berger (1995), based on the autobiography of Milankovitch, but widened in scope by remarks of the son Vasko Milankovitch. The book contains facsimiles of the exchange of fascinating letters between Milankovitch, Köppen and Wegener on a variety of themes. The most important one was naturally the timing of insolation changes and the impact or changes of the geometry of the orbit of planet Earth around the sun on climate changes between glacials and interglacials during the most recent geological past (Milankovitch, 1941). But Wegener and Köppen also influenced Milankovitch's thinking on the causes of changes of the planetary magnetic field and its consequences on the paleopositions of poles ("movement of the poles" according to Berger, 1995) in the geologic past (with the ensuing consequences for the "Origin of Continents and Oceans" and their paleogeography). Together with Wegener he speculated a lot about the physical state of the interior of the Earth's interior and the causes of the changing magnetic field.

Milankovitch lived 1879–1958, hence he was junior to Köppen who was born in 1846, but born only shortly before Wegener's birth in 1880. He died 13 years after the end of the World War II. He endured as a Serbian citizen the hardships of the World War I which — however — provided him with the privilege to work after a short time as Austrian prisoner of war on his hypothesis of the relationship of the changes of the geometry of the earth's orbit around the sun. They had both encouraged Milankovitch, a Serbian engineer, to pursue this idea. He had studied in Vienna, had won many good friends in Austria who finally succeeded to get him out of the POW camp. He was then confined to the building of the Hungarian Academy of Sciences in Budapest, where he could work scientifically. He published his calculations extensively many years later (Milankovitch, 1941).

Köppen had contacted Milankovitch through letters since 1922 from Hamburg (Berger, 1995) but then Wegener, Köppen and Milankovitch met in person 1924 at a conference in Innsbruck (88th Conference of the “Gesellschaft deutscher Naturforscher und Ärzte” and paid each other personal visits after the Wegener- and Köppen- families had moved from Hamburg to Graz. The new book of Köppen & Wegener (1924) about “Climates of the Geological Past” was about to be published and Wegener gave an extensive talk about his hypothesis of the “Origin of continents and oceans” as well as about his ideas on reasons for the climatic changes between Glacials and Interglacials. Milankovitch was deeply impressed that Wegener attended so much to his ideas. About a decade later, at an INQUA congress in Vienna Milankovitch was cornered by Albrecht Penck who together with Bruckner had defined the late Quaternary subdivision of the Alpine Glacials and Interglacials, mainly based on morphologic and geological arguments (Penck and Bruckner, 1909) and who was not willing to accept Milankovitch’s arguments.

THE REVIVAL OF THE MILANKOVITCH HYPOTHESIS DURING THE LATER PART OF THE 20TH CENTURY

The Milankovitch-hypothesis to explain Quaternary Glacial and Interglacial climate variability was not very much in the public limelight for a long time, mainly because the accessible paleoclimatic archives (deep-sea sediments, ice cores, lake sediments, loess deposits) could not be dated with sufficient precision. It was the revolutionary paper of Hays et al. (1976) on data from two southern Indian Ocean sediment cores, which were dated precisely and allowed the authors to prove the presence of the three dominant Milankovitch frequencies in the time series of the proxy data, which triggered the revival of the Milankovitch hypothesis.

Actually, its validity was hotly debated at first (and in some circles still is, see Karner and Muller, 2000) because it is believed that 1) the influence of the Milankovitch frequencies on the insolation changes is considered to be too weak to cause large climatic changes, 2) there is no real explanation of the 100 kyr-cycle (eccentricity, cf. Berger, 2012) and 3) thresholds and the cascades of processes in the climate system are too poorly known (Schellenhuber, 2009). However, this changed dramatically with the advent of modern dating techniques which allowed to “translate” the available stratigraphies into time series of climate relevant proxy data.

Approx. 40 years ago Hays, et al. (1976) published their evidence for the presence of Milankovitch cyclicity in deep-sea sediments (see also Maslin, 2016) and revived a hypothesis which can be traced back to the early decades of the last century (Köppen and Wegener, 1924). Berger (1988) then published an excellent review of the relationship of the Milankovitch theory and climate and put its history into a historical context (Berger, 2012). The regular pace of the alternations of Glacials and Interglacials tempted people to model ice ages, climate cycles and the transitions between these two end members of the late Quaternary climates (Paul and Berger, 1997) who related them to the global carbon cycle and Shackleton 2000 seems agree to this conclusion.

Evidence from deep-sea sediments and ice cores

Nowadays the orbital parameters originally calculated by Milankovitch can be substantiated by means of time series obtained from deep-sea sediments (Hays, et al., 1976) and ice cores (Augustin et al., 2004) for the past. Milankovitch frequencies can also be quantitatively calculated/predicted for the future and are hence a powerful argument when debating future climatic scenarios (Thiede and Tiedemann, 1998). Consequently, this reflects an important piece of tradition in the development of our understanding of how climate evolved in the course of time, reaching from Köppen, Wegener and Milankovitch to modern days. The latter aspect is probably the most important scientific contribution of the book of Köppen and Wegener (1924) (however, see further below).

Imbrie et al. (1993) widened the scope of the Milankovitch theory and considered the structure and origin of major glaciation cycles.

They discussed in particular the impact of the 100 000 year cycle which was considered to be far too weak to generate the large climate fluctuations, but found that “local responses over the 100 000 year cycle are similar to those of the shorter Milankovitch frequencies implying that similar internal climatic mechanisms operate in all three of them”. In detail, they documented that the last deglaciation was a clear response to orbital forcing. Rutherford and D’Hondt (2000) observed the important change of the pace of ice ages between 1.5 and 0.6 ma concluded that increased heat flow across the equator “triggered the transition to sustained 100-kyr glacial cycles”.

Imbrie et al. (1993) then extended their considerations over a two-million-year long time interval and detected that the dominance of the 100 000 year cycle was restricted to the younger part of the Quaternary. Further back in time it diminished and the dominance of the obliquity and precession related cycles became more important in controlling insolation, for reasons not clearly understood. They also define a substantial list of unresolved questions, namely of the physical mechanisms driving the orbitally forced responses to Milankovitch-driven changes in insolation or the feedbacks which drive the 100 000 year cycle. Also the question how the Milankovitch driven cycles were interacting with cyclic processes which operate at higher frequencies, was left unresolved.

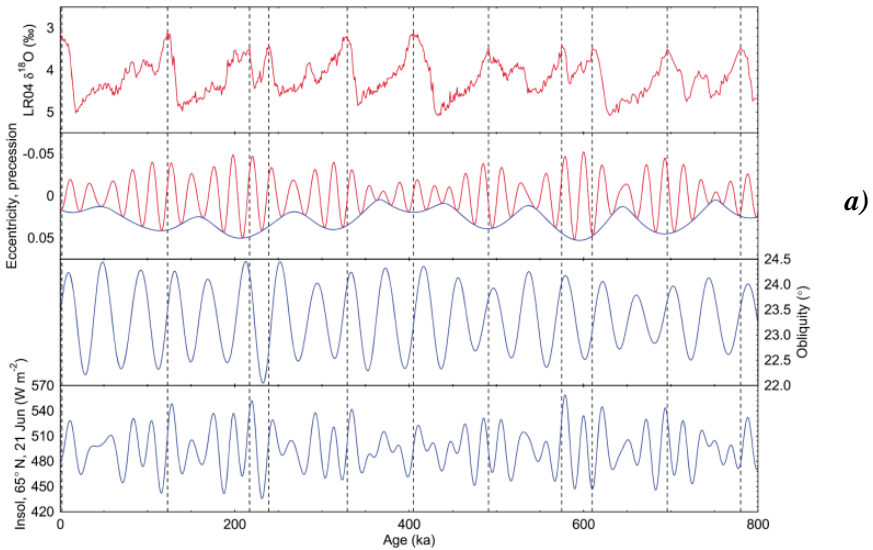
CYCLOSTRATIGRAPHY AND THE MILANKOVITCH THEORY AS DOCUMENTED IN SEDIMENTS OF PRE-QUATERNARY PERIODS OF THE PHANEROZOIC

The discussions of the Milankovitch theory by Berger et al. (1988, 2012) and Hays et al. (1976) motivated colleagues studying cyclic sedimentation patterns originating from periods of the Phanerozoic other than the Quaternary in the context of their Milankovitch frequency control. It actually led to a revival of the hypothesis of the Milankovitch control of sedimentation patterns, because many formations consisted of sedimentary sequences with apparently cyclic repetitions of their individual layers, making it tempting to look for the cause of their cyclicity. This is not the place to cover this aspect completely, but it seemed important to point to the fact that Milankovitch frequencies and their impact on climatically sensitive depositional regimes can be observed during many times, both in marine as well as in terrestrial environments. Schwarzscher (1993) also considered a number of different “geological oscillators” which could generate cyclic sedimentation patterns, namely one related to the planet system, the other one related to self-oscillating systems, possibly related to the climate system.

As described in Schwarzscher (1993), cyclic sedimentations patterns or “cyclostratigraphies” have been observed in Precambrian to modern depositional environments. To link them to or maybe explain them by environmental changes caused by Milankovitch frequencies encounters several problems, namely sufficiently precise dating of sections as well as plausible causal explanations. The stratigraphic data need to be dated

precisely before they can undergo transformation into time series and be subject to spectral analysis. In addition, Berger (1989) found out that precession has grown in duration from 16–19 kyrs during the Silurian to 19–23 kyrs during the Quaternary, obliquity 27–30 kyrs during Silurian to 42–54 kyrs during the Quaternary; he explained this to be due to the decreasing day length and the continuously increasing earth - moon distance.

Examples of cyclic sedimentation pattern which could have been caused by environmental change in response to Milankovitch frequencies have been found in marine, lacustrine, evaporitic and fluvial environments. Famous are the Jurassic marl-limestone cycles (Seibold, 1951) in Germany, the shale-limestone cycles of the Mesozoic (Schwarzacher and Fischer, 1982) or the cyclic sediments of the lacustrine Green River Formation (Eocene) in the US (Fischer and Roberts, 1991). However, how the cyclic sedimentation patterns caused by transgressions and regressions along continental margins (Vail, et al., 1991) can be linked to Milankovitch frequencies, remains another open problem.



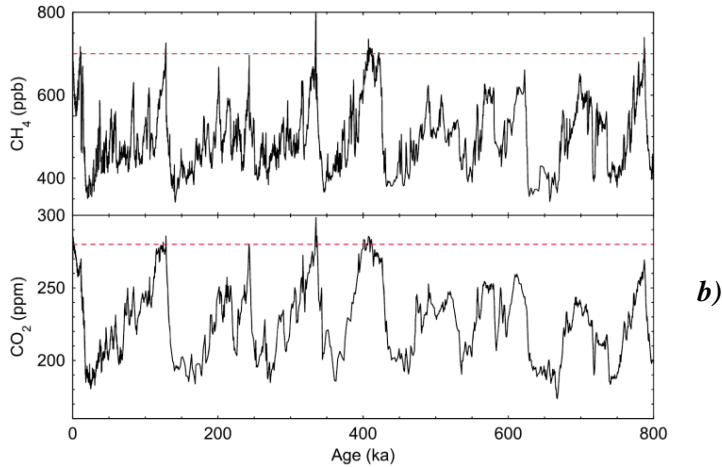


Figure 10: Complex data set of Past Interglacials Working Group of PAGES, 2016: a) identification of interglacial peaks and insolation parameters, and b) concentrations of atmospheric greenhouse gases over the last 800,000 years, based on measurements in Antarctic ice cores

MODERN INSIGHTS INTO THE MILANKOVITCH-FREQUENCIES AND THEIR IMPACT ON CLIMATE CHANGE

The foundations of paleoclimate research laid by Wladimir Köppen and Alfred Wegener are expanded today in many laboratories worldwide. 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.

The understanding of paleoclimate processes and global linkages are fundamental to assess potential future developments. 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.

Andre Berger (1988, 2012) has revisited this entire complex in modern times. The Milankovitch frequencies of the orbital parameters control insolation; they can be calculated precisely for the past and for the future. Recently the Past Interglacials Working Group of PAGES (2016) led by A. Berger have compiled a complex data set about the duration and properties of the Interglacials over the last 800 000 years (Fig. 10) and they came to the following conclusions: 1) Transitions from Glacials to Interglacials (socalled Terminations) “involve rapid, non-linear reactions of ice volume, CO₂ and temperature to external astronomical forcing”, and 2) ”The combination of minimal reduction in northern summer insolation over the next few orbital cycles, owing to low eccentricity, and high atmospheric greenhouse gas concentrations implies that the next glacial inception is many tens of millennia in the future”.

CONCLUSIONS

Orbital parameters have long been suspected to have a major impact on climate variability. But it was M. Milankovitch who systematically investigated their properties and introduced their obvious impact into the past climate variability.

The congenial cooperation of Köppen, Wegener and Milankovitch resulted in a revolution of our understanding of timing and mechanisms of the late Quaternary climate variability.

The advent of modern dating techniques of climate archives in ice cores, deepsea, lake and loess sediments finally resulted in the definition of the Milankovitch frequencies in historic records (in a geological sense).

The scientific legacies of Wladimir Köppen and Alfred Wegener are also pursued at the Alfred-Wegener-Institute, Helmholtz Center for Marine and Polar Research in Bremerhaven (Germany), Wegener Center for Climate and Global Change, an interdisciplinary and internationally oriented institute of the Karl Franzens University, Graz (Austria) and the recently founded Köppen-Laboratory of Geochronology at the State University of Saint Petersburg (Russian Federation).

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grandgrandson of Wladimir Köppen and hence the grandson of Alfred Wegener), as well as from Dr. Chekin (Moscow and Springfield/VA-USA, a distant relative of the Köppen-family) and Dr. Snigirevsky (director of the SPbGU field station on Crimea). The caretakers of the archives of the AWI, of the BSH and of the DWD as well as the director of the library of Saint Petersburg State University Marina Karpova, were extraordinarily helpful by providing information, in particular pictures. Two unknown Russian referees pointed out minor mistakes in the manuscript.

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CLIMATE CHANGE AND WATER RESOURCES: THE OUTCOME OF COSMIC CYCLES, TECTONIC SHOCKS, AND INDUSTRIAL DEVELOPMENT

HANS PETER NACHTNEBEL

University of Natural Resources and Life Sciences, Muthg. 18, A-1190, Vienna, Austria

E-mail: hans_peter.nachtnebel@boku.ac.at

Abstract. Climate variability is the result of external forcing like solar irradiation but it depends also on terrestrial processes like volcanic eruption, internal global feedback mechanisms such as the interactions among climate and vegetation cover, and on anthropogenic forcing acting on water and climate directly. In this paper, the main climate cycles are described and characterized with respect to their periodicity and their impacts on global earth temperature and on water resources systems. The anthropogenic forcing over the last 150-170 years on climate and water resource systems are discussed and compared with long term patterns extending over millenia. Finally, conclusions with respect to the time horizon of water resources management strategies are drawn.

Key words: Cyclicity, Temporal scales, Climate change, Human impacts, Water resources, Vulnerability

1. INTRODUCTION

Our climate is driven by orbital forcings due to Milankovic cycles, volcanic processes, internal feedback mechanisms between climate, water bodies and vegetation, and human activities [1]. The observed long term changes in climate, from which the glacial cycles are the most prominent ones, are obviously reflected in changes of the global water cycle, such as the storage of huge amounts of freshwater in glacial systems and sea level changes during freezing and melting periods. Stochastic processes like volcanic eruptions have modified longterm climate trends by release of CO₂ and ashes which interferred with solar irradiation and radiation balance of our globe. But most prominent, human activities during the last 150 years impacted directly on climate resulting in an increasing trend in greenhouse gas concentration (GHG) and in consequence leading to an

increase in global temperature of about 0.9°C [1], an increase much larger than found for deglaciation periods.

Human activities have also modified the hydrological flow paths of water at several spatio-temporal scales by the implementation of physical structures to manage water distribution and storage, even beyond catchment boundaries. It is worth to consider that both the catchment boundaries, especially in the lower part of the basins, and large scale storage schemes, like glaciers and extended groundwater systems, were formed within large scale temporal cycles initiating glaciation and deglaciation processes. The main task of water resources management is to satisfy human water requirements to mitigate adverse impacts originating from spatio-temporal variability in access to water resources. In other words, the natural variability in availability of water has to be balanced by engineering measures. The strategy to achieve this task is to analyse data series, usually extending over a period of about 50-100 years, to fit a model and to derive design values for future management strategies. This means that stationarity is assumed, at least implicitly, and our designed systems are expected to perform well over a period of about the next hundred years. For protective measures, like spillways of large reservoirs, design values for a return period of about a few thousand years are needed.

To be able to quantify the various impacts originating from internal and external drivers the magnitude and time scales of changes are briefly described. First, longterm solar cycles are described, then short term solar activities are analysed, and finally human induced climate changes are quantified.

2. SOLAR IRRADIANCE AND CLIMATE CHANGE

The greenhouse effect of the atmosphere has been scientifically explained by Fourier, about 200 years ago, was confirmed by measurements by Tyndall, about 170 years ago, and fully quantified by Arrhenius [2], about 125 years ago. It is evident that the “natural content” of greenhouse gases (GHG), like water vapor, methane, CO_2 has already contributed in the past to the radiation and energy balance of our globe like a greenhouse keeping part of the incoming solar radiation and warming up the atmosphere. For our globe, this effect was estimated to 33°C resulting in a mean surface temperature of 14°C .

2.1 Solar irradiation, long-term cycles in CO₂ concentration, and climate change

Analyzing longer time periods of several 10 ka (ka is thousand years) there is high confidence [1] that orbital forcing due to Milankovic cycles is the primary external driver of glacial variation. It is mainly a reduction in northern hemisphere (north of 60⁰) summer insolation that generates sufficient cooling to initiate ice sheet growth [3] but atmospheric CO₂ needs to be considered as an internal feedback mechanism. During interglacial periods, the atmospheric CO₂-concentration was higher compared to glacial periods. In Fig. 1 the orbital forcing due to Milankovic theory are compared with atmospheric CO₂-content obtained from proxy data over the last 800 000 years. It is worth to note that recent CO₂ concentration, and especially its fast increase is much larger. The mean rate of increase in global surface temperature ranged between 0.3 - 0.8 °C/ka, while during faster increases in temperature a rate up to 1.5 °C per ka was estimated [4]. Even this rate is much lower than the recent increase found in observation corresponding to 0.9 °C within 150 years. The Milankovic cycles are generated by gravitative interaction among planets on their orbit resulting in deviations from a two-body problem, like orbit of a single planet around the sun. Due to superposition of cycles a variability in the intensity as well as sub-cycles are detected. For our planet, we observe orbital eccentricity with cycles of 413 ka plus 95 ka and a 125 ka periodicity while the obliquity cycle is given with 41 ka years. In the axial precession a cycle of 112 ka years has been identified (Fig.1 and Table 1). Changes in eccentricity and axial tilt (obliquity) affect the seasonal and latitudinal distribution and magnitude of solar irradiance. The dominating factor is obliquity, because the amplitude of the seasonal variation in the solar radiation is directly proportional to obliquity. However, such forcing, without consideration of CO₂ concentration, would not be sufficient to lead to large-scale deglaciation. Obviously, the recent global average figures of CO₂ with 410 ppm are substantially higher compared to data in Fig. 1.

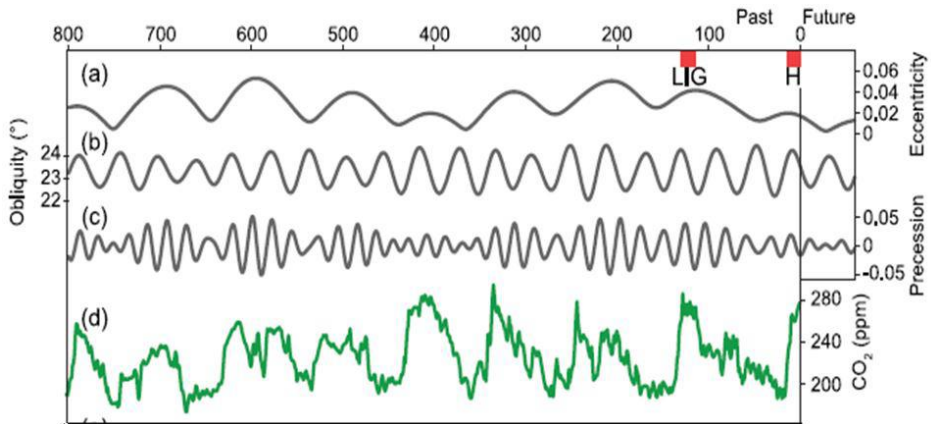


Figure 1: Milankovic cycles over the last 800 000 years and related atmospheric CO₂ content [1] Orbital parameters and proxy records over the past 800 ka. (a) Eccentricity (b) Obliquity (c) Precessional parameter (d) Atmospheric concentration of CO₂ from Antarctic ice cores [5]

Table 1: Milankovic cycles due to orbital forcings

Orbit	Periodicity
Eccentricity	413 ka, 95 ka and 125 ka
Obliquity	41 ka
Axial precession	19 ka, 22 a and 24 ka
Apsidal precession	112 ka

2.2 Stochastic processes like volcanic eruptions and climate

Volcanic forcings occur randomly but exhibit a spatio-temporal clustering. Such eruptions release large amounts of SO₂, ashes and CO₂ into the atmosphere (Fig. 2 and Fig. 4) and determine the climate at the annual and multi-decadal time scale. These events are followed by regional to large scale temperature drop downs of the earth surface by 0.1-0.3 °C for several years, mainly due to an increase of aerosols. Examples are given in Fig. 2 showing the impacts from severe eruptions in 1258, 1453, and 1815 [6, 7, 8]. See also Fig. 4.

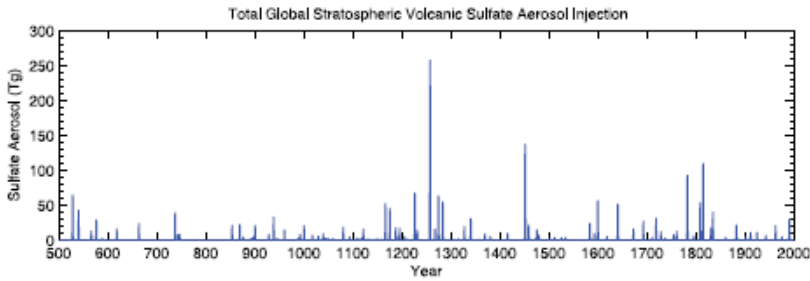


Figure 2: Annual stratospheric sulfate aerosol injections from year 500-2000 [9]

2.3 Cycles due to solar activity

Several other climate cycles are reported that are explained by either solar activities and/or by internal cycles related to extent of glaciation, linkage to ocean currents and feedback of vegetation cover. It should be also considered that the terrestrial geomagnetic field exhibits a variability influencing incoming radiation.

Numerous cycles are listed in [10] ranging from decades to millennia. Some of them are modulated in their intensity, some are clustered meaning that when they occur they exhibit the identified period but longer periods without such events may happen, like for instance in the de Vries-Suess cycle. In general, these periodicities are attributed to solar magnetic activities. The database for analyzing solar activities is based on cosmogenic isotopes taken from sediment samples and ice cores, supplemented by observations of sunspot numbers and detailed measurements of cosmic radiation in the younger past.

During the last few decades, a decrease in solar activity has been observed accompanied by a quiet solar minimum. That is contrasting to the very intensive five previous cycles that could be classified as a grand maximum [11].

Sun spot number and the dependent short-term solar irradiance vary within a cycle of 11 years. During the last cycles the total solar irradiance varied by about 0,1 %. Over longer periods of about 210 years, grand solar minima, each lasting for about 50 – 100 years [12], are reported. Typical examples are the Maunder minimum (1645-1715) that coincidences

roughly with the Little Ice Age, and the less pronounced Dalton minimum from 1795-1825.

The Gleissberg cycle with a period of 88 (85+-15) years has been found in several solar-terrestrial records and could be detected over the last 12 000 years [13]. This process is directly linked to a multiple of the sunspot cycle. The amplitude of the Gleissberg cycle is modulated by the de Vries-Suess cycle over a 2 000 years period.

The de Vries-Suess cycle [14], exhibiting a 250 years period, is also found in ^{14}C , in ^{10}Be data and other cosmogenic radionuclides, as they were also found in the Gleissberg cycle. The periodicity is confirmed for the whole last ice age back to about 100 ka [15]. It is the reason for the occurrence of the grand minima [16] in solar activity. Both, Gleissberg and de Vries-Suess cycles are generated by solar forcing. Analysis indicates that global warming during the last 150 years is much stronger than the influence from these orbital forcing.

The Dansgaard-Oeschger events detected in ice cores exhibit a cyclicity of about 1 470 years with a deviation of less than 100-200 years [17]. In the Northern hemisphere these rapid climate oscillations are characterized by a fast increase in temperature followed by its long slow decay. The reason for this cycle together with the Heinrich stadials is not fully agreed within the scientific community but pure solar forcing is doubted. It is assumed that the internal global feedback mechanism, such a glaciation processes and thermohaline north Atlantic currents, triggered by the superposition of the cosmic cycles discussed above, could be an explanation [18]. In total, 25 events were identified during the last glacial period associated with an increase of temperature of about 5-8 $^{\circ}\text{C}$ within about 40 years.

The Hallstatt cycle with a return period of 2 000 to 2 400 years has been also detected in radio-carbon data attributed to solar activity [19, 20]. This cycle is seen as a long-term change in solar activity with grand minima and maxima clustering around the minima and maxima of the Hallstatt cycle. This long-term oscillation can be also explained by Milankovic's theory because the revolution of Jupiter, Saturn, Uranus and Neptun around the sun exhibits a repeating pattern with a period of 2 318 a [21]. This dynamic process has an impact on the inertial motion of the sun, acts on solar activity and would modify the incoming cosmic ray flux to earth.

Table 2: Cycles due to solar activity

Name/activity	periodicity	deviation
Sun spot number	11 a	
Gleissberg cycle	88 a	+ - 15
de Vries-Suess cycle	250 a	
Dansgaard-Oeschger	1 470 a	
Hallstatt cycle	2 200 a	+ - 200

2.4 Internal variability due to bio-physical-chemical feedback

The long cycles in the solar irradiation, especially in its regional distribution, initiate a series of feedback processes because of formation of large ice sheets that in turn change ocean circulation and large scale atmospheric wind systems. In addition, changes in the vegetation layer are relevant for accumulation or release of CO₂. In general, the water-, Carbon-, Nitrogen-, and Oxygen cycles are essential for explain sub-cycles generated by external forcing.

Wang et al. [22] analyzed stalagmites in a cave in central China and derived a time series of 224 000 years characterizing the pattern of East Asian Monsoon events. Then, Wang *et al.* [23] developed a global and regional Monsoon concept proving that Monsoon intensity and duration of hydrological events, were dominated by eccentricity-modulated-precessional cycles of 22-23 ka, similar to the glacial periods on the Northern hemisphere. The frequency of Monsoon events increased during glacial increase while the duration decreased. The regional features like land-ocean configuration and topography and temperature gradients dominated the Monsoon patterns with much shorter variability.

Ocean currents and global wind systems are generated by large scale differences in solar energy input, by differences in salinity, and by vertical temperature gradients in parts of the oceans. The North Atlantic oscillation (NAO), the Atlantic multidecadal oscillation (AMO) and the Atlantic meridional overturning circulation (AMOC), and El Nino Southern Oscillation (ENSO), they characterize main features of the ocean currents. Seip et al. [24] found for the first three indicators a common oscillation within 30 -+ 11 years in which the NAO index showed a very low performance while AMOC showed the strongest

signal. Shorter cycles within 7 to 20 years were also detected but with a low significance. The dominating role is changing among these ocean current indicators. The El Nino events occur in general every two to seven years with the hottest years occurring during these periods. These events are accompanied by extreme weather conditions which, in their characteristics, are dependent on regional conditions.

2.5 Industrial development and climate trends

During the last 150 years, there is an increasing trend in mean surface temperature running in parallel with an increase in total greenhouse gases. The mean globally averaged land and ocean surface temperature has been increased during 1880-2012 by about 0,85 °C [1] with a faster increase since 1980 (Fig. 4). The mid- and long-term increase in some GHGs is given in Fig. 3, indicating a pronounced increase since about 1850.

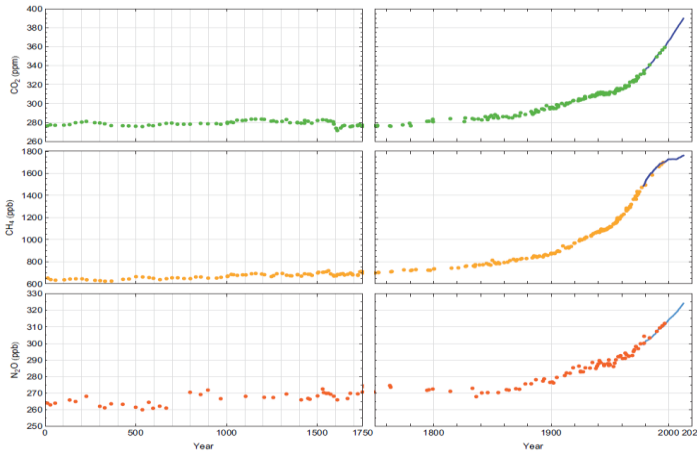


Figure 3: Atmospheric CO₂, CH₄, and N₂O concentrations history over the industrial era (right) and from year 0 to the year 1750 (left), data obtained ice cores (color symbols) and from direct atmospheric measurements (blue lines) [1]

The trend in anthropogenic emissions led to GHG-concentrations exceeding the highest values over the last 800 000 years, as found in ice cores [1]. Also the rate of increase has not been observed during the last 22 000 years. According to IPCC [1] there is high confidence that a longterm cooling trend over the last 5000 years in the mid to high latitudes of the Northern hemisphere [25] is being compensated and even reversed by human activities over the last 150 years. During 1950 and 2000, four

of the five warmest decades have been observed in our 2 000-year-long reconstructed temperature time series. The 10 years period from 1999-2008 was the warmest of the past 200 decades. Temperatures were about 1.4°C higher than the projected value based on the linear cooling trend.

Over the last decades in the 20th century the five solar cycles can be described by very intensive maxima or perhaps a Grand maximum [16; 11] followed by a declining phase since about 2 000. The recent solar cycle minimum is characterized by a very low intensity in sun spot activities. A comparison of the various forcings on the global surface temperature is given in Fig. 4 considering solar variability, volcanic contribution, anthropogenic impacts and internal processes, such as El Nino oscillations. The anthropogenic component includes the emission of GHGs plus the cooling components from aerosols, like in the volcanic component.

In Figure 4, the main drivers of climate are compared in their intensity of temperature change. The cyclicity in the solar component is clearly visible; the volcanic contribution is relevant in the short term but it decays within a few years; the internal variability due to feedback cycles and processes like ENSA or NAO, is quite large but is obvious that the observed increase in mean global temperature is mainly driven by the anthropogenic component. As pointed out already above, we are now in a long-term cooling process since about 2 000 years. Due to the short time window long-term processes as Milankovic cycles are not visible here.

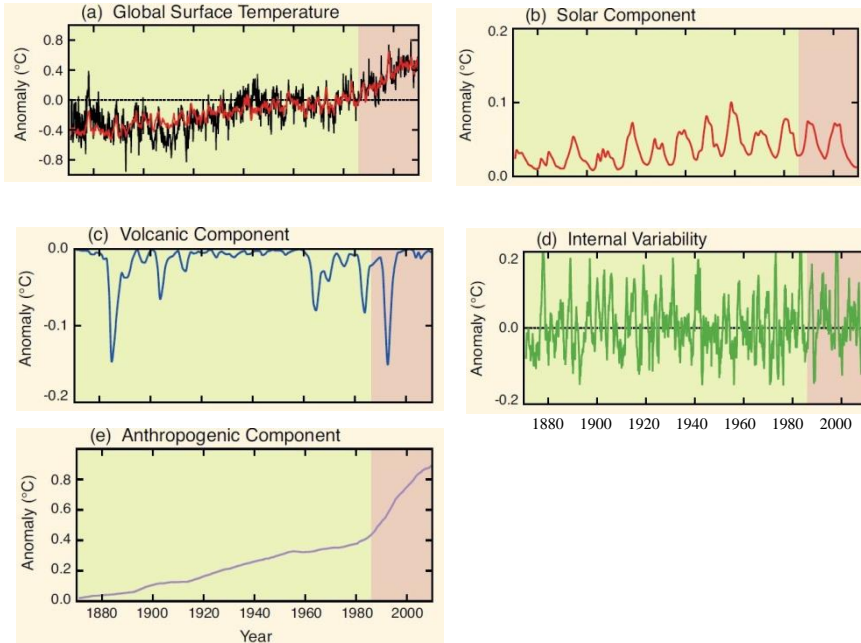


Figure 4: Global surface anomalies and some of their components (natural, anthropogenic from IPCC [1] p. 393). black measured, red sum of (b) to (e)

3. IMPACTS ON WATER SYSTEMS

All the previously discussed drivers of climate change are also reflected in their impacts on water resources in its spatio-temporal features, and also on the hydrological processes. The Milankovic cycles have driven glaciation and deglaciation processes associated with sea level changes and severe modification of landscapes. According to [1] „there is high confidence that maximum global mean sea level during the last interglacial period was, for several thousand years, at least 5 m higher than present level“. Also, during interglacial periods higher average precipitation and glacier melt contributed to a high sediment transport capacity resulting in formation of large deposits of material in the low lands. These processes shaped the catchment boundaries and created large groundwater systems [26]. The variations in magnetic susceptibility and grain size distribution of sediment layers, taken in Hungarian plains from 500 m boreholes, coincidence with Milankovic cyclicity of 40 and 100 ka period.

Although recent orbital forcings are favourable for glacier growth in the Northern hemisphere the opposite, a shrinking process, is observed [1] during the last 100 years. There is high confidence that annual mean surface warming since the 20th century has reversed long-term cooling trends of the past 5000 years in mid-to-high latitudes of the northern hemisphere. Based on tree ring analysis and sediment data, it can be concluded with high confidence that during the last millennium severe droughts occurred in many regions, often more severe than today, as documented by Cook et al. [27], for North America. There is also agreement, that during the last millenium larger flood events than recorded have happened in Europe [28] (see also Fig. 7), eastern Asia and in the western Mediterranean region. In other regions, like India [29] and north America, the floods observed since 1950, are with high probability exceeding historic events of the last millenium.

3.1 Human impacts on the water balance

Besides climate change impacts on the water cycle, which are manifold and complex to assess at the regional scale, also direct human impacts on the water resource system are essential. The quantitative human impacts refer to land use changes, and to engineering measures to provide storage capacity and to change the flow paths of water, all of them associated with increasing consumption. Additionally, water flow is always connected with the transport of materials, like sediments and therefore any intervention into the flow paths of water is associated with erosive and depository processes. Subsequently, a few examples of quantitative changes in water flows will be given, demonstrating the intensity of direct human impacts on water resources. Accompanying very relevant impacts on river morphology, environmental impacts and ecosystem services have to be neglected here.

Huang et al. [30] estimated that agricultural production requires about 85-90 % of global freshwater from which about 70 % can be allocated to irrigation techniquies. Due to droughts and seasonal disharmony between demand and availability reservoirs have been developed since several thousand years. Globally, there are millions of dams offering an aggregate storage capacity more than 8 300 km³ [31]. A comparison of artificially stored water with storage in natural freshwater bodies ranges between 4 % to 10 % [32; 33]. The inundated area due to reservoir constructions is estimated at 754 550 km² corresponding to about 2,5 % of naturally

covered freshwater surface. According to ICOLD [34], about 50% of the reservoirs serve irrigation, while about 20 % of the dams are primarily used for flood control purposes and 25 % are operated for hydropower generation. It should be considered that numerous reservoirs are operated as multi-purpose schemes.

Due to water abstraction and reservoir operation, the mean annual discharge has been decreased in many river basins and sometimes even the seasonality in runoff has been reversed downstream. An example is given in the runoff pattern of Colorado River (Fig. 5). The decrease in mean annual discharge occurred within about 50 years due to water abstraction and climate variability. Similar trends are found in the discharge pattern of the Nile [36; 37] indicating a sudden decrease in both discharge and sediment load after 1900 due to the implementation of the Aswan Low Dam and even more pronounced after 1965 when the Aswan High Dam was put into operation. Ludwig et al. [38] estimate the decrease of total freshwater inflow to the Mediterranean Sea by about 20 % between 1960-2000, mostly driven by water abstraction and partly by climate change.

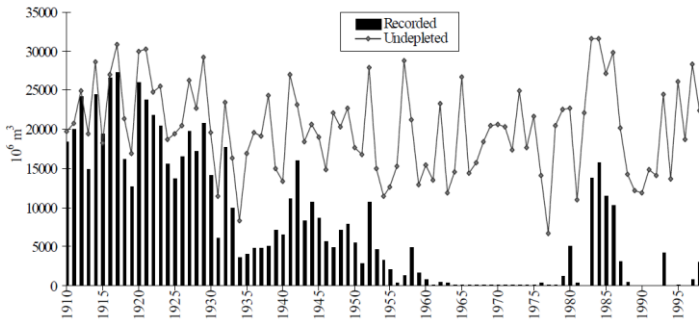


Figure 5: Annual discharge of Colorado River at the Southerly international boundary (1910-1998) [39]

Similar trends are detected especially in endorheic basins, like lake Chad in central Africa shrinking by 95 % within 1963-1998 [50], decrease of lake Urmia in Iran by about 80 % within a short period from 2009-2015, severe lowering of water table in the Dead Sea in near East, and the most dramatic example refers to Lake Aral (Fig. 6). From a lake that covered in 1962 an area of about $65,9 \times 10^3 \text{ km}^2$ only about 10% remained, separated into small water bodies exhibiting a high salinity [40]. Although the weight of driving factors is different in each case the direct human intervention is identified as the main driver. A global overview of regional

trends in the water balance is given for the period 1984-2015 in Pekel et al. [41].



Figure 6: Changes in lake area of Aral Sea [40]

Not only the surface water flows have been modified due to water and land management but also the vertical flows were changed. Gordon et al. [41] showed by comparing potential vegetation cover with actual coverage that due to large-scale deforestation water vapor flows have been reduced by about 4 % while expanded irrigated land increased the flow by a somewhat smaller but similar quantity. Although the net balance has been only slightly decreased, the spatial flow pattern has been drastically modified. The linkage among modified vapor flow and precipitation rates, thunderstorms and the decrease of regional temperature is not yet fully understood but impacts of land use on climate exist on local and regional scale, especially in the Asian monsoon system. A good example is the Sudd wetland along the Upper Nile River. This area of more than 30×10^3 km² is exposed to at least seasonal flooding. Besides of its high ecological value it also smooths the Nile discharge and augments runoff during low flow periods. Several projects had been proposed to drain this huge area to reduce evaporative losses. Mohamed Y.A. et al. [43] analyzed in detail the linkage between evaporation losses and the regional climate and concluded that regional relative humidity will drop by about 30-40 % during the dry season accompanied by a substantial temperature increase.

3.2 Human impacts on extremes and its impacts

Impacts from floods have increased tremendously over the last decades [44; 45; 46]. As pointed out by Jongman et al. [47], flood damages are the most frequent and costliest natural hazard. The respective economic damages are about \$19 billion/an [48] and more than 115 million people/an are affected globally. This fact is surprising because many countries, especially in Europe, have annually invested substantial

amounts in physical flood protection measures, such as levees, dykes and flood detention reservoirs. In addition, additionally it is worth to consider that very likely that there is no trend in increasing flood frequency at the global scale.

The IPCC report on extreme events [49] concludes that there is limited to medium evidence available to assess climate driven observed changes in the magnitude and frequency of floods at regional scales. Further, there is low confidence at the global scale regarding even the sign of the changes, except an expected increase for the earlier spring flow in snow-dominated regions, at least in Europe and Asia. With high confidence, floods larger than recorded since the 20th century occurred during the past five centuries in northern and central Europe, the western Mediterranean region and eastern Asia. An example from Vltava River (Fig. 7) yields a similar picture. It shows no trend neither in catastrophic nor in extraordinary flood events. In some smaller basins, a trend in flood frequency cannot be excluded because of river engineering works and losses in natural retention capacity. Nevertheless, the main reason for increasing flood damages is seen in inadequate land development in former flood plains neglecting the residual risk.

The anthropogenic droughts, when water stress is caused or intensified by human activities, became also visible in the last decades. The shriking of large continental water bodies like lake Aral and others has been discussed already above. Williams et al. [51] analyzed anthropogenic forcing in droughts in the south-western US and quantified the resulting warming effect by about 47% of the severity of the last mega drought between 2000 and 2018, besides other drivers such as ENSO-effect. Also, the large-scale drainage of wetland areas has modified the atmosphere-land surface coupling that (may) aggravate regional drought intensities.

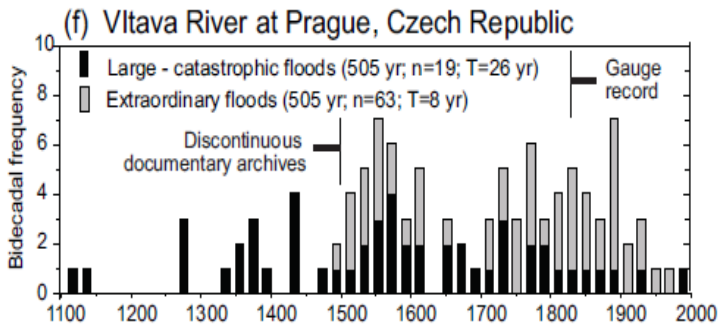


Figure 7: Vltava River combined documentary and instrumental flood record at Prague [27] discharge thresholds: CAT, flood index 2 and 3 or discharge $>2900 \text{ m}^3/\text{s}$, EXT flood index 1 or discharge 2000 to $2900 \text{ m}^3/\text{s}$

4. SUMMARY AND CONCLUSIONS

Milankovic cycles are the primary external drivers of glacial variation due to a reduction in northern hemisphere (north of 60°) summer insolation that generates sufficient cooling to initiate ice sheet growth. These cycles extending over several millennia (19 - 413 ka) formed the physiographic structures of our catchments including catchment boundaries, drainage systems and natural storage capacity. Stochastic events, such as volcanic activities, trigger the global climate over periods of a few years up to a decade. Within the last 150 years, human activities resulted in an increase of GHG concentrations increasing at a faster rate compared to changes during the last 800 ka, and exhibiting also a higher level. The global water resources are driven by these climate changes, although several feedback mechanisms have to be considered, and by direct anthropogenic impacts due to land use changes and development of large-scale water infrastructure.

Quantifying the various drivers over several ka it can be concluded that the anthropogenic forcing on both climate and water resources dominate recent changes at several scales. While the impacts on climate are measurable at the global scale, the changes on the water cycle during the last 100 years are greater in several regions than the impacts of global warming, especially in Asia, the western US, and in semi-arid regions. Only over larger time scales, associated with glaciation-deglaciation processes, greater changes in land cover are documented. Further pressure on water resources is expected due to ongoing land use and the climate change.

An important task for water management is in upgrading coastal defense structures, as in the last four decades the global mean sea level was raised by 0.19 m and this process will very likely continue at a rate of more than 2,5 – 3,6 mm/an. In addition, the design of spillways requires revisions, having in mind that in several regions like in India, Near East and North America larger floods than observed may happen (medium confidence). Flood levees should be equipped with release structures to avoid frequent failures due to uncontrolled overtopping and subsequent collapse. Guidelines harmonizing land development and flood risk need to be implemented and enforced at the basin scale. Although no visible global trend in flood frequency has been confirmed, the reported damage are quickly increasing due to a lack of such guidelines or its missing enforcement. Land use changes, accompanied by climate change, result in overexploitation of regional water resources and desertification of large areas. Some examples for anthropogenic droughts are the shrinking/disappearance of large continental water bodies, such as lake Aral. Natural water storage capacities should be preserved, virtual water exports should be reduced and water use efficiency needs improvement. Large-scale drainage will aggravate regional drought intensities, as has been demonstrated for the Sudd in south Sudan and in south-western US.

Several design quantities for protective hydraulic structures are based on return periods from several hundreds to even thousand years, such as the design of coastal defense structures, levees in densely populated areas and the design of spillways of large dams. Even when most of the identified climate cycles exhibit long periodicities some of them exhibit shorter cycles and become effective at least in a regional trend in water balance within a few hundred years. Usually, our statistical tools in hazard analysis assume stationarity, neglecting trends and cycles, and this assumption is not valid anymore. In such an unsteady environment, also the term return period becomes meaningless. In parallel, the design and operation of large reservoirs needs to consider such long-term trends and increased variability in inflow, as already pointed out by Hurst, about 60 years ago. The Milankovic cycles are beyond the time horizon of engineering measures but some of the shorter cycles are reflected as a long-term trend in our time series, covered by other triggering effects.

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Part II: What have we learned from Milanković's theory ?

ASTRONOMY AND CLIMATE: OLD AND NEW IDEAS

DIDIER PAILLARD

Laboratoire des Sciences du Climat et de l'Environnement, Orme des Merisiers, Centre de Saclay, 91191 Gif-sur-Yvette, France

E-mail: didier.paillard@lsce.ipsl.fr

Abstract. The idea that climate is strongly linked to astronomical cycles can be traced back to antiquity and the invention of the calendar. Still, if the effect of daily and annual cycles on temperatures are obvious, the role of longer cycles on climate was strongly disputed during the 19th and the beginning of the 20th centuries in the context of Quaternary glaciations. Milanković's genius allowed to establish a strong foundational theoretical background, that ultimately allowed to demonstrate the influence of astronomy on glaciation cycles. Today, some pieces are still missing in the puzzle of ice age cycles, most notably the mechanisms and the role of atmospheric pCO₂ changes and the transition towards larger and slower cycles after the Mid-Pleistocene transition. The links between astronomy and climate are certainly not restricted to the question of ice-sheet changes, and Milanković was also pointing at the important role of the precessional forcing at lower latitudes. It is now well-known that the hydrological cycle in many semi-arid and monsoon areas is strongly linked to precession. These climatic changes are largely independent of glaciations, and it is worth underlining that the stratotype for the Quaternary is in fact linked to Mediterranean sapropels. Cyclostratigraphy is now a standard tool for geologists, but the many links between astronomy and climate are still not well understood. For instance, the strong 400-ka periodicity found in carbon isotopic records during the last 200 million years has probably far-reaching consequences on the Earth's climate dynamics.

Key words: Milutin Milanković, History of science, Climatology

1. INTRODUCTION

The discovery of ice ages in the nineteenth century was the starting point of scientific discussions on the mechanisms of climatic change. Indeed,

after geologists found clear evidences of glaciations in many different places in the world, some physical explanations for such large-scale climatic changes were needed. Astronomers were actually quite reticent to discuss this topic and the very first astronomical theories were developed by non-academic people like Joseph Adhemar in 1842 or James Croll in 1864. Geologists like Archibald Geikie in 1863 or James Geikie in 1874 observed that a succession of glaciations occurred in the past. Though this was in agreement with an astronomical theory of ice ages, other scientists were more in favour of a mechanism involving internal oscillations in the Earth system between climate and the carbon cycle. For instance, Chamberlin in 1897 suggested such an oscillator and Svante Arrhenius attempted the very first computation of the effect of atmospheric CO₂ on the Earth temperature, in order to reinforce this theory.

In this context, Milankovic was the first to provide a solid mathematical framework to explain the role of the variations of the orbital parameters of the Earth on our climate. This proved to be critical to the understanding of Quaternary paleoclimatic records, in particular when the chronology of ice ages became sufficiently robust in the 1970's. The famous paper by Hays et al., 1976 [5] is therefore often presented as a “proof” of Milankovic's theory, though the situation is in fact significantly more complex.

Indeed, it is now well established that the pace of Quaternary glaciations is directly linked to orbital forcing, but the main periodicity observed during the last million years is not associated to obliquity changes at 41 kyr, as expected by a simple interpretation of Milankovic's theory, but it appears strongly linked to eccentricity changes at 100 kyr. Over the last 40 years, many scientific publications attempted to address this so-called “100-kyr problem” (see for instance [15]). On the other hand, before the Mid-Pleistocene transition (MPT) that occurred about 1 Myr BP, the dominant periodicity of glaciations was indeed 41-kyr, just as expected by Milutin Milankovic. It can therefore be stated that the Milankovic's theory of ice ages, in its simplest version, works quite well during the early Pleistocene, but no so well after the MPT. In order to account for ice ages during the late Pleistocene (a time period sometimes called the “100-kyr world”), it is necessary to specify some internal dynamics for the ice-sheet and climate system, that may possibly also involve the carbon cycle. Over this time period, ice ages are more easily understood in terms of an internal

oscillator forced by the astronomy, a view that tends to provide a synthesis between the two different opinions expressed in the 19th century on this topic: either an external astronomical forcing or an internal oscillation.

But geologists have now considerably enlarged their knowledge since the 19th century and it is today much too restrictive to limit the role of astronomy to the ice age problem of the Quaternary. Indeed, the astronomy is clearly impacting climate even when no ice-sheet is present, through many different mechanisms, some being rather well understood and others being still rather mysterious. The best known example is the low latitude precessional forcing of monsoons and more generally of low latitude precipitations. Such a signal was expected by Milankovic, since he clearly stated that precession should have a much larger role at low latitudes, while ice-sheet and high-latitude climate should depend mostly on obliquity. The basic mechanism is also quite well understood, since monsoons are directly affected by the summer heating of the continents, itself linked to the insolation forcing. More generally, the inter-tropical convergence zone (ITCZ) moves globally according to precession, since continents are more abundant in the northern hemisphere. In some specific areas, this leads to spectacular results. The best example is probably the Mediterranean sapropels that provide a precise chronology over the last 10 to 15 million years [10].

Based on these successes, cyclo-stratigraphy is now a standard tool in geochronology. But when looking at longer periodicities, it becomes a challenge to identify the physical mechanisms linking the recorded geochemical or climatic changes with astronomy. An intriguing example is the pervasive 400-kyr oscillation found in carbon isotopes over at least the last 200 million years, and the possibility that these cycles are further modulated by longer periodicities, most notably 2,4 Myr and also 8 to 9 Myr [2, 12]. The persistence of these orbitally-forced oscillations over such a long time period may point towards some fundamental connection between our Earth climate and astronomy that remains to be deciphered.

2. QUATERNARY GLACIATIONS

Astronomical theories of climatic changes were first applied to the problem of glaciations in the 19th century. The early theories of Adhemar and Croll were based mostly on precession. Indeed, scientists were quite aware that the duration and intensity of seasons should change in relation

with the precession of equinoxes, also known as “the third movement of the Earth” since the Antiquity. Milankovic mathematically demonstrated that obliquity had a much more important effect on high latitude and that the summer season should be considered as the most critical one. But astronomical seasons have varying durations and it is not entirely trivial to choose a “summer insolation” in a relevant way for the ice age problem. For this purpose, Milankovic defined “caloric seasons”, with the caloric summer being the half year receiving the largest amount of solar radiation at the top of the atmosphere. This forcing is largely dominated by obliquity. In the 1970’s, it became more usual to use the summer solstice daily insolation (usually taken at 65°N, the latitude of northern ice-sheets). This forcing has a more important amount of precessional content, a feature that may be more favorable to explain the recent glaciation cycles. Interestingly, it was also suggested recently to use the sum of the insolation forcing above a given threshold, as a surrogate of a “positive degree day” forcing classically used by glaciologists [8]. This new definition of “summer insolation” is again dominated by the 41-kyr obliquity cycle and happens to be quite similar to the original suggestion of Milankovic.

Still, choosing the right forcing is not sufficient. As explained in Hays et al. [5], glaciations are “paced” by the astronomy. We now can go further and state that Milankovic did correctly predict the “41-kyr world” that is observed between about 3 Myr BP and 1 Myr BP, when ice ages are clearly driven by obliquity changes. But after the MPT, the main cyclicity appears to be linked to eccentricity [5]. There is currently no consensus on the mechanisms behind these longer and larger oscillations, but the concept of relaxation oscillations has many advantages (see eg. [3]). Indeed, in such a framework, it becomes easier to explain the rather stable amplitude of glacial oscillations while the astronomical forcing is strongly modulated by eccentricity at 400-kyr. In such a framework, it is rather natural to switch from one astronomical frequency (41-kyr) to another one (100-kyr) when some other external parameter varies slowly [14] and thus to explain the MPT.

In this concept, a key element is that the triggering of deglaciations is in some way linked to the ice-sheet being sufficiently large [14, 23]. Several possible underlying mechanisms have been suggested to explain this [17]. One possibility is that larger ice-sheet might be less stable than smaller ones. In particular, the ice near the base of the ice-sheet will be warmer or

will even start to melt. This will significantly accelerate the flow of ice and it is possible that such a large ice sheet could disintegrate rather rapidly. This dynamical process was actually one of the first suggestion made by glaciologists to explain the so-called “100-kyr problem”. Another option was suggested by climate modelers [4] involving the surface albedo of large ice sheets. Indeed, the larger the ice-sheet, the drier the climate above it and the surface ice will receive little fresh snow, but possibly higher amounts of dusts. If the albedo of fresh snow is very high, it becomes much lower through aging and, of course, even lower when loaded with dusts. It is therefore possible that the glacial maximum favours a rapid surface melting of such an ice-sheet thanks to lower surface albedo. Another suggestion to explain a causal link between large ice sheets and deglaciations happens through deep ocean circulation and atmospheric CO₂ [18].

Indeed, bottom waters are currently formed mainly on the Antarctic continental shelf, with brine rejection of sea ice having an important role. If this mechanism should be enhanced during glacial times because of stronger sea ice formation and stronger winds, it should nevertheless completely break down when the Antarctic ice-sheet covers the whole continental shelf, as suggested by geological reconstructions, a few thousands of years after the last glacial maximum. This stop of the “sea ice factory” allows for a de-stratification of the ocean and the release of CO₂ in the atmosphere, thus favouring global warmer climates as observed just before the last deglaciation. Finally, it is also important to mention the possible role of rapid climatic variability in the terminations. Indeed, if the deep ocean circulation has several equilibria as suggested by numerous studies, then there might be a connection between the deglacial “switch” mentioned above and the oceanic abrupt changes. Obviously, it is also possible that each one of the above processes has some important role in the dynamics of ice ages and that they should all be accounted for in a more realistic description of ice ages.

Glaciations are “paced” by astronomy, but obviously the dynamics involved in the recent ice age cycles is far from being understood as a simple response to this forcing. Whatever the detailed mechanism, it appears now that some internal dynamics of the Earth system has a critical role in the ice age problem, in particular in order to explain the 100-kyr cycles and the MPT. During the 19th century, scientists disagreed on the nature of ice ages, being either externally induced by the astronomical

forcing or being an internal oscillation of the Earth system. Today, both views have gained some value and the idea of an externally forced “internal” relaxation oscillator has gained some credibility [18, 20]. An open question remains the exact role of CO₂ changes in these cycles. If Milankovic has correctly predicted the “41-kyr world” many decades before it was observed, it should also be reminded that Arrhenius correctly predicted the last glacial maximum CO₂ to be about 30 to 40% lower than preindustrial levels, almost a century before it was measured in Antarctic ice cores. Furthermore, during deglaciation, there is a clear lead of a few millenia of the CO₂ rise with respect to the melting of ice-sheets [15]. It is therefore difficult to avoid the idea that pCO₂ might have some role during terminations.

Unfortunately, current climate models are not well suited to address these questions. A key difficulty in simulating ice-sheets is the long time-scales involved (at least tens of thousands of years) and the small spatial scales for a good representation of ice flows (kilometers or smaller). These icesheet models need furthermore to be coupled with the atmosphere above, in order to provide a climate consistent with the evolution of the ice sheet, but also these need to be coupled with the ocean below, since large ice sheets like Antarctica today also have ice-shelves that are key elements of their dynamics.

A fully coupled model of the atmosphere, the ocean, the carbon cycle and ice sheets with all these relevant processes is still not feasible today, though some interesting progresses have been obtained with Earth Models of Intermediate Complexity (EMICs) [4, 25].

3. ASTRONOMY AND CARBON CYCLE

But as outlined above, the influence of the astronomical forcing is not limited to ice-sheets. An intriguing enduring feature of geological records is the pervasive 400-kyr oscillation observed in Earth ¹³C records over much of the Cenozoic and possibly before [6, 19]. These oscillations are often used as a cyclo-stratigraphic target to build age scales and the international geological time scale now relies on these ¹³C cycles at several specific time periods. These cycles are also clearly visible during the last few millions of years as shown on figure 1, though their connection with eccentricity appears more complex during the last part of the Quaternary than during the preceding millions of years. Indeed, most

of the time during the Cenozoic, high values of eccentricity are associated with low values of ^{13}C on Earth. Over the last million years, this connection is perturbed, probably as a result of the large glaciations that occur during this time.

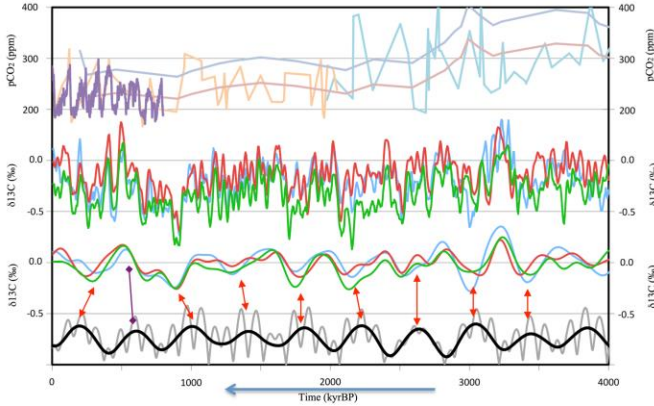


Figure 1: At the top : $p\text{CO}_2$ data from Antarctic ice cores in purple [11], boron isotopes. In orange and light blue [7, 1] and the envelope of alkenone isotopes [21]. Middle : marine ^{13}C records from [24, 13, 22] and the corresponding filtered values at 400 kyr (bandpass = 2.5 Myr $^{-1}$). Bottom : eccentricity [9] and the corresponding filtered values. Adapted from [16].

Global ^{13}C reflects the balance between volcanic or kerogen sources, and biogenic or carbonate sinks. It appears very difficult to explain such a large amplitude oscillation through changes in inorganic processes alone while organic carbon burial or kerogen release might more easily account for such an oscillation. A reasonable hypothesis is therefore that the precessionnal forcing has a direct impact on the net balance of organic matter burial and kerogen release, with high forcing leading to enhanced monsoonal precipitations and kerogen erosion, thus explaining the carbon isotopic signal. This was demonstrated in the conceptual model [16] whose results are presented on figure 2. Interestingly, such a mechanism induces changes in Earth carbon cycle that might account for a long-term oscillation in the atmospheric $p\text{CO}_2$ of about 20 ppm, a magnitude compatible with our knowledge from Antarctic ice cores. As a consequence of this astronomical forcing, the 2 – 2,4 Myr amplitude modulation of the eccentricity is clearly appearing in the carbon model results, in agreement with observations from long marine $\delta^{13}\text{C}$ records [2, 19]. In particular, according to this concept, it is worth mentioning that the long-term modulation of eccentricity may thus induce a drop in the surface Earth carbon content, and therefore a drop in atmospheric CO_2 and in temperature, at to specific times over the last millions of years: at about 2.8 MyrBP, roughly in correspondence with the start of Quaternary

glaciations, and also at about 0.8 MyrBP, in close connection to the MPT and the enhancement of glaciation cycles.

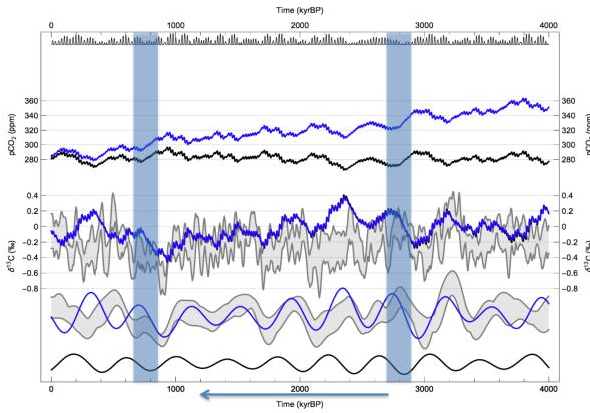


Figure 2: Top: precessional forcing used as an input of the model. In black, the model results in terms of pCO_2 and $d13C$ for the standard simulation, and in blue, the results when a downward trend is added in the carbon content of the Earth. The range of the $13C$ data from figure 1 is shown in grey shading.

Bottom: the filtered $d13C$ results and data and in black the filtered eccentricity. The blue vertical areas indicate the start of the Quaternary glaciations (about 2.6 or 3 MyrBP) and the Mid-Pleistocene transition (0.7 or 1 MyrBP). These two time periods seem to be linked to the long-term modulation of the carbon cycle model, and therefore could be linked to long-term eccentricity modulation. Adapted from [16].

This model is obviously much too crude to represent faithfully the intricate mechanisms involved in the astronomical forcing of the carbon cycle. Still, it highlights that finding new connections between the astronomy and climate are not only a possibility, but a necessity. Furthermore, this could pave the way towards explaining many important questions on longer-term climate variations during the Cenozoic or even the Mesozoic. In any case, the 400-kyr cycles in the carbon cycle are a reality that deserve a much closer attention from the climate and geochemistry modelling community.

5. CONCLUDING REMARKS

Milankovic's contribution to Earth Science was tremendous and actually went far beyond the astronomical theory of ice ages. Interestingly, he was neither a geologist, nor an astronomer. He was trained as a civil engineer and started his early career by building bridges and dams. One of his major scientific achievements can be described as building the first bridge between two rather separate areas of science: geology and meteorology on one side, which were very empirical at that time; and mathematics and physics on the other side, with a strong mathematical background. We

need to follow his tracks and continue to build such bridges between communities.

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WHAT GEOLOGISTS THINK ABOUT CLIMATE CHANGES- TIME IS RELATIVE

DEJAN RADIVOJEVIĆ

*University of Belgrade - Faculty of Mining and Geology, Department of
Regional Geology, Kamenička 6, 11000 Belgrade, Serbia*

E-mail: dejan.radivojevic@rgf.bg.ac.rs

Abstract: The time measuring was probably one of the first things people learned and has been known since ancient Egypt 1500 BC. Besides importance for mankind the time flow is a basic function of many sciences, including geology. Milanković cycles theory has enabled geologists to investigate the past but is also most important part for prediction of future global climate. The significance of Milanković's work for geology is numerous, knowing that it represents the basics for cyclostratigraphy, which enables more precise time determination and calibration between the astronomical and geological time scale. The determination of climate conditions that prevailed during certain geological period is one of the geological tasks. During geological past, the hot and cold periods interchanged several times, while the Cenozoic Paleocene-Eocene Temperature Maximum is an excellent analogue for today's global warming situation. People have managed to recognize their influence in global warming and in recent years a lot of attention has been focused on reducing the negative human effect on climate changes.

Key words: Milanković, Cyclostratigraphy, Astronomic time scale, Geological time scale, Climate changes.

1. INTRODUCTION

There is a big difference in the understanding of the time flow among ordinary people and those who deal with geology. In their work, geologists usually encounter fossils and rocks that are hundreds of millions of years and even billions of years old. At the other side ordinary people are very often impressed by several centuries-old artifacts or historical events from several decades ago. For these reasons, it can be said that geologists have a very clear notion of the time relativity. An additional confusion in the already complex situation brings the fact that

in the Serbian language the same word is used for the time and weather conditions.

In recent years, climate changes have been a heated debate both, in the media and scientific circles. People has 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 attack and were forced to adapt to the new business conditions [1, 2, and 3]. Very often people equate climate with weather conditions. That is why today we can often hear stories in the media about climate change without considering time interval that separates those two. Geologists belong to the group of scientists who are very aware of this difference and the fact that the climate has changed in the past. Our planet has repeatedly gone through various periods from the stage of Snowball Earth to the fireball Earth. Yet despite these dramatic condition changes, life on Earth has been ongoing since it first appeared 3.5 billion years ago. It has always found a way to win, while successful adaptation to the new conditions was the key.

The great Serbian scientist Milutin Milanković, and his cycles theory [4], enabled us to understand the mechanism and reason for climate change. The greatest influence on geology is probably represented by the Astronomical (Milanković) calibration of the geological time scale (GTS) [5, 6]. His astronomical theory of climate change is the base of cyclostratigraphy [7] a subdiscipline of stratigraphy that deals with determining, characterizing, correlating and interpreting cycle changes in the stratigraphic record. The main goal of cyclostratigraphy is application in geochronology by improving the accuracy and resolution of the time-stratigraphic framework.

2. GEOLOGISTS AND THE CONCEPT OF TIME

The planet Earth is 4.54 billion years old and it was believed that the first primitive organisms appeared in the Cambrian (542 million years ago) while the life before that time (during the Precambrian) did not exist. Now we know that first microorganisms appear much earlier (at 3.5 billion years), but the division into Precambrian and Phanerozoic (of which the Cambrian is a part) is still applied.

The usual human understanding of long period of time mainly refers to years or several decades, which is the reason for the lack of a sense of measuring time in millions and billions of years. For these reasons, an understanding of the Precambrian that lasted more than 4 billion years is inconceivable to the common man. If the age of the planet were shown on the clock, the Precambrian would last longer than 21 hours and make up 88% of the geological time (Figure 1). For geologists who study the Earth, its origin, the processes that shaped it and its composition, ancient excavations and archaeological discoveries represent recent events. The period from the first appearance of humans until today is a blink of an eye for geologists, and it would take one minute and seventeen seconds on the 24-hour clock (Figure 1).

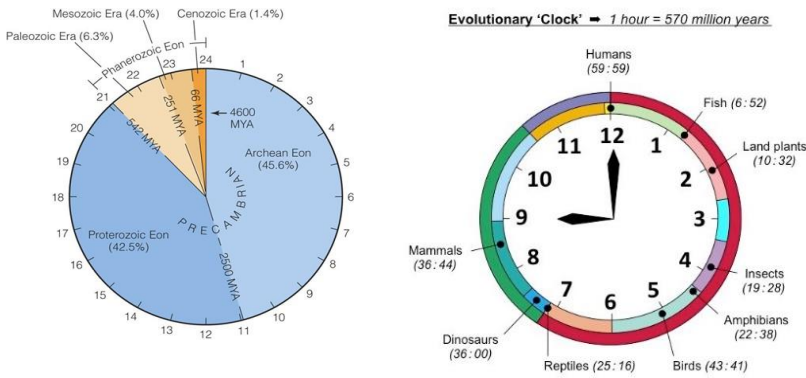


Figure 1: Geological time of planet Earth given at 24-hour clock (left), the evolutionary clock from Phanerozoic Eon until today given on one-hour clock (right).

3. HOW MILANKOVIĆ'S CYCLES HELPED GEOLOGISTS

A precise geological time scale is necessary to understand and decipher the evolution and geological processes of our planet. Milanković cycles are the basis of cyclostratigraphy, one of the youngest stratigraphic disciplines which deals with the determination, characterization, correlation, and interpretation of cycle changes in the stratigraphic record. It uses astronomical cycles of known periods to determine the time of the sedimentary record. The main goal of cyclostratigraphy is increasing the accuracy and resolution of the time stratigraphic frame. Milanković cycles provided an understanding of the last ice age and represent the most important part for the development of a high-resolution astronomical time

scale (ATS). In addition, they are a good basis for creating a forecast model of climate changes that awaits us in the future.

The most significant of astronomic cycles are Milanković cycles (precession, obliquity, and eccentricity) which result in perturbation of the Earth's orbit and its rotational axis and have periods ranging from 20 to 400-kyr (Figure 2). These cycles via orbitally induced changes in insolation influence climatic, oceanographic, sedimentary, and biological changes that are potentially preserved in sedimentary records over geological time.

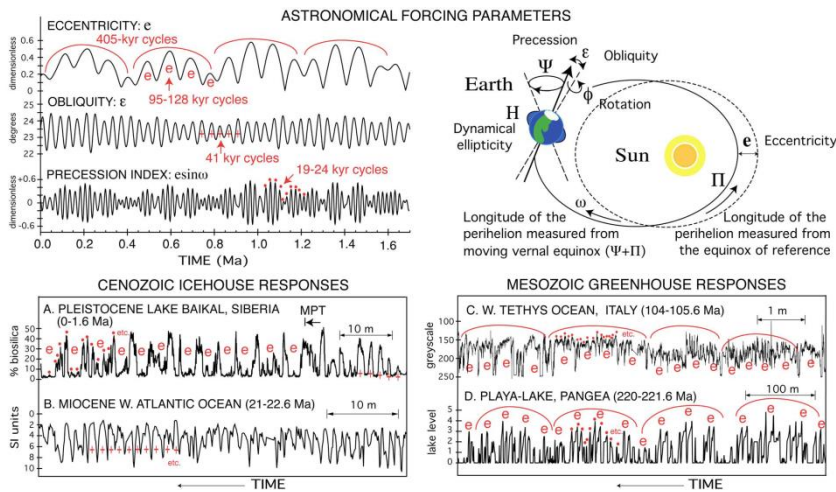


Figure 2: Parameters affecting Earth-Sun position (top right) and oscillations shown for past 1.6 million years (top left) [8]. Main periodicities are indicated in red. Continental and marine sedimentary sequences showing icehouse (bottom left) and greenhouse (bottom right) climate responses. A- Lake Baikal core [9], B –ODP site 936B core [6], C- *Fucoid Marls* core [10], D – *Newark Series* core [11].

Cyclostratigraphy search for evidence of climate change that corresponds to solar cycles which are found in sedimentary rocks layers (Figure 3). It is used to study the stratigraphic and sedimentological response to climate change. At the heart of this method is the recognition of layers according to their glacial or interglacial characteristics, and the translation of a stratigraphic profile or record into a time scale or series. It is important to note that the sedimentation rate spatially and temporary varies and that it depends on palaeoecological and paleogeographic conditions. Generally, fine-grained and more rounded material reflects calm and slow sedimentation, while coarse-grained, angular materials are probably

related to fast sedimentation and the existence of short palaeotransport. This create a good starting point for a detailed reconstruction of the conditions under which the given sediments were formed. The reworked sediments, bioturbation, erosions, hiatus (interruptions in sedimentation) could complicate interpretation and can lead to misinterpretation.

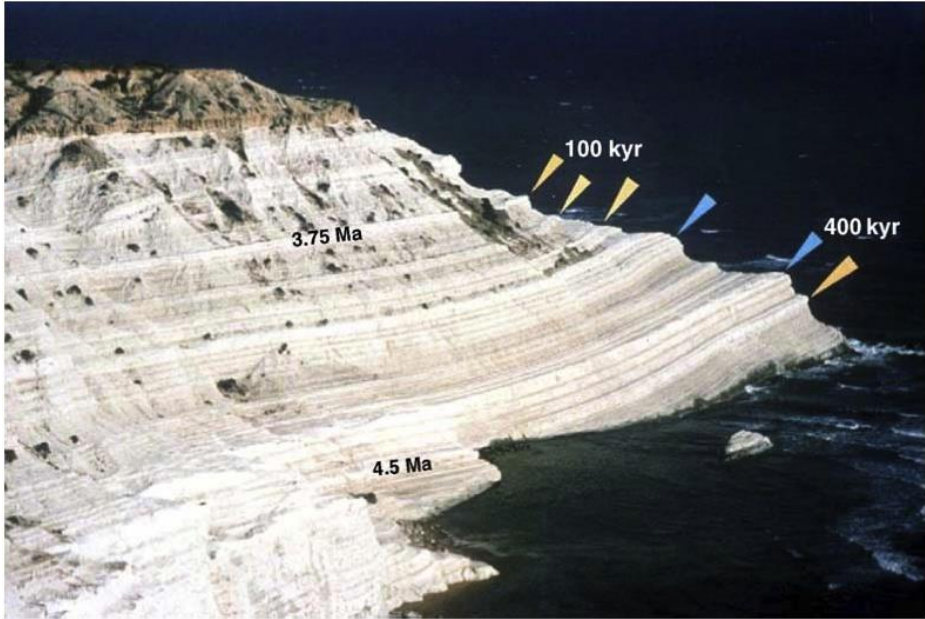


Figure 3: Example of Milanković's cycles at geological section in Spain.

The cyclostratigraphy made a great ascent in last thirty years. Over the last decade, astronomical theory has been successfully applied to a continuous high-resolution GTS correlation. The astronomical tuning method advances traditional geological dating methods, such as paleontology, paleomagnetism, and radioisotope dating. On the GTS 2012 [12] most of the Cenozoic era was directly calibrated with the ATS (Figure 4).

ATS based on Milanković forced stratigraphy calibrated with paleoclimatic 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 [13] examined Milanković cycles in the Lower Permian strata in southern China are time-calibrated with high-precision U-Th dating. 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. This is the first significant piece of evidence in defining the Paleozoic ATS, which is based on absolute time and thus connect the Paleozoic-Mesozoic transition.

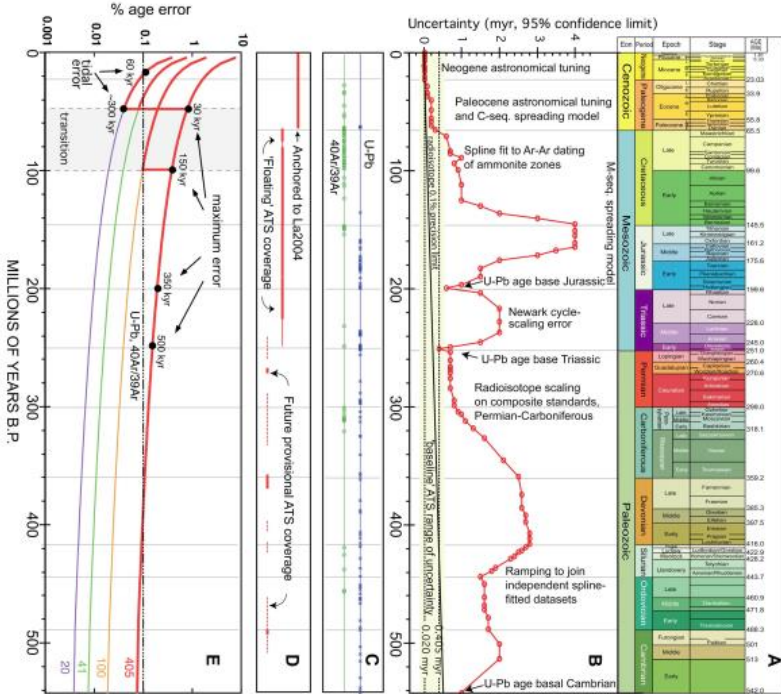


Figure 4: Uncertainty in the Phanerozoic International Geologic Time Scale (GTS) 2004 [14]. A- Standard GTS division. B- Estimated uncertainty (95% level of confidence). C- Distribution of U-Pb and 40Ar/39Ar. D- distribution of astronomically forced cyclostratigraphy during Phanerozoic. Thick solid lines 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.

4. CLIMATE CHANGES IN THE GEOLOGICAL PAST

When you mention global warming to geologists, they may reciprocate by asking you what global warming you mean. If you mention today's global warming to them, they will tell you that we are currently in the interglacial period of the ice age. All in all, it can be said that for geologists, time is relative both in terms of the flow of time and in terms of weather conditions (in Serbian the same word is used for period of time and

weather). In the history of our planet, there have been much warmer as well as much colder periods than today.

The five most important glaciations from the geological past 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 Quaternary (2.58 million years today) (Figure 5). In the last million years, a dozen glaciations have occurred, from which the largest one was 650,000 years ago and lasted 50,000 years. The last glacial period reached its peak 18,000 years ago, before the beginning of the Holocene interglacial.

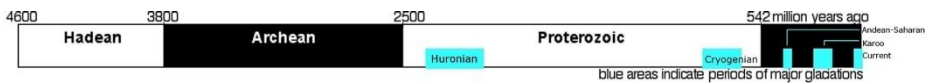


Figure 5: Timeline with five most important glaciations marked in blue. Between them are greenhouse conditions.

The planet Earth has undergone through warm (greenhouse) and cold weather conditions (icehouse) several times (Figure 6) during its history. The greenhouse period, in which Earth has been 85% of time (Figure 5), is a time when there are no continental glaciers and the level of carbon dioxide and other greenhouse gases (including water vapor and methane) are high.

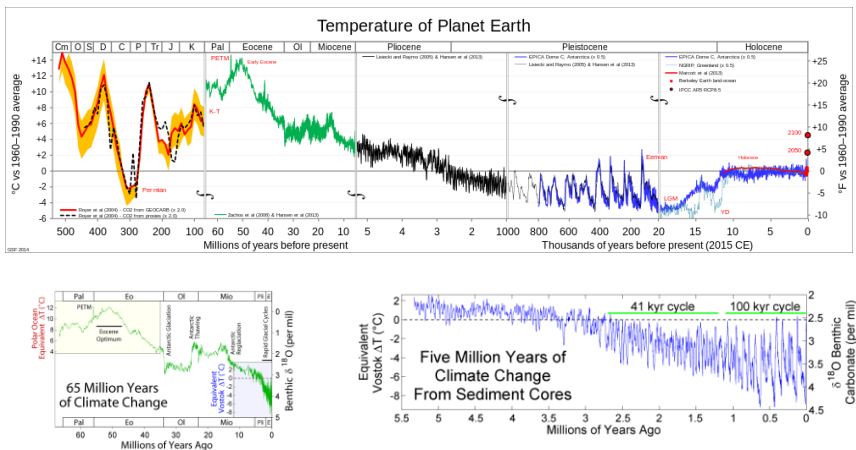


Figure 6: Assumed temperature- from the Phanerozoic to the present (top), the Cenozoic to the present (bottom left) and in the last 5.5 million years (bottom right).

There are several theories about the greenhouse Earth origin. The sedimentology record contains data on a high carbon dioxide levels and other greenhouse gases in the geological past. For example, during Ordovician Period (485.4-443.8 million years), the amount of carbon dioxide was 14-16 times higher than today. What is known for sure is that the plate tectonics was very active during the greenhouse period. Due to the disintegration of continental plates (rifting), volcanic activity was significantly more pronounced, producing more carbon dioxide and warming the Earth's atmosphere. In the last 500 million years, the Earth has spent more than 80% of time in a greenhouse condition.

The Earth's icehouse are periods in which there were at least two ice sheets on the planet, at the poles, the Arctic, and the Antarctic. These covers increased and decreased during a shorter times known as glacial periods (with the formation of additional ice sheets besides to the two at the poles) and interglacial periods (without additional ice sheets). During the icehouse period, greenhouse gases are less present in atmosphere and temperature show a global decline. The Earth is currently in a cold period that began 33.9 million years ago with the beginning of the Late Cenozoic Ice Age. The part of this ice age is the last glacial Würm, which was recently completed (115,000 -11,700 years) and left behind the still present non-polar ice sheets in the Alps, the Himalayas, Patagonia, etc. This period will probably be followed by another interglacial that will be similar to the last known one (Eemian, 130-115,000 years ago), during which we had warm temperature forests in Scandinavia, while animals of today's African continent characteristics inhabited Western Europe. After that, the periods of glacial and interglacial, that will have the same lengths as the previous ones, will continue to alternate until the two ice sheets at the poles disappear, which will mark the end of the icehouse and the onset of the next greenhouse period.

The reasons for the icehouse are hotly debated, because essentially not much is known about the transitions between these two climate states and the reasons that lead to it. Certainly, one obvious reason is the evident reduction in carbon dioxide presence in the atmosphere due to decreased volcanic activity. Another significant reason is plate tectonics activity which influenced the opening and closing of ocean passages. 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. An example of this event is the opening

of the Tasmanian Passage (36.5 million years ago), separating Australia and Antarctica, which together with opening of Drake Passage between South America and Antarctica is believed to have caused the Cenozoic ice age. At the other side, 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. Additionally, tectonic activity forms mountains (for example Himalayas, about 50 million years ago) and the formation of new soil that acts as a carbon dioxide absorber significantly affects the amount of greenhouse gases in the atmosphere.

Despite the widespread opinion that harsh temperature conditions (no matter high or low) would lead to mass extinction, the ability to adapt to different environments influenced the fact that during extremely high temperatures on our planet ruled the largest reptiles ever, while in the period of intense glaciation lived the largest known mammals (Figure 7). The Pleistocene (2.58-0.012 million years ago) is generally recognized as a time of land mammalian gigantism.

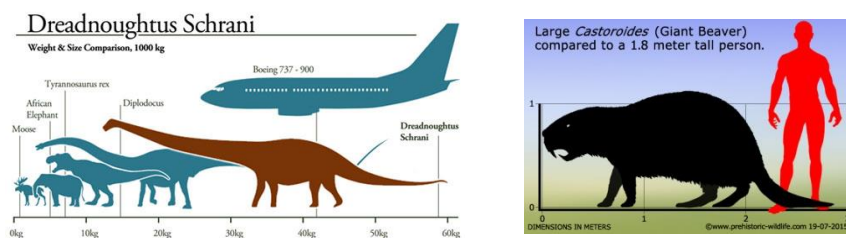


Figure 7: Examples of gigantism during Cretaceous high-temperature (left) and last ice age (right).

In general, it can be said that climate changes have the greatest impact on organisms that live in shallow seas, since the expansion of glaciers or the flooding of their ecological niches are the first one to be hit.

5. THE CLIMATE – WHAT AWAITS US

The Paleocene-Eocene temperature maximum (PETM) is of special importance for climatologist since it represents the excellent analogue for climate prediction modelling. It is calculated that by year 2300 the concentration of carbon dioxide in the atmosphere will exceed 2000 ppmv [15] 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 (55 million years ago) and

led to intense global warming. The increase of carbon dioxide emissions into the atmosphere, which in 2011 exceeded 390 ppmv [16], has not been recorded in geological history. The climate and biogeochemical response to such a rapid and large increase in carbon dioxide in the atmosphere will be very harsh (heatwaves, droughts, floods), especially on continents that are settled at high 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 [17, 18, and 19]. 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. Based on foraminifera analyzes a similar situation was confirmed during PETM [20, 21].

6. CONCLUSIONS

The age notion and duration of certain periods in the history of the planet Earth has so far been mainly solved based on paleontological fossil records, magnetostratigraphy and radioactive decay of certain elements. The greatest progress in recent years has been made with the help of an astronomical time scale and its calibration with a geological time scale. The basis of the astronomical time scale as well as one of the newest geological sciences – cyclostratigraphy are Milanković cycles.

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. Unfortunately, human impact and emissions of carbon dioxide and other greenhouse gases, deforestation and other technogenic activities are accelerating this otherwise natural process. In general, it can be said that what will happen to the climate in the future is not a novelty, but a repetition of conditions that were present in the geological past of the planet before. Nevertheless, although it is believed that the harsh conditions caused by climate change lead to mass extinctions, life has always managed to adapt to the new conditions. It is certain that the human species will not be the first to be hit by climate change, just as it is certain that it is the only one that is aware of its impact on accelerating this process. Therefore, increasing public attention and a large amount of intellectual and financial resources are focused on activities to reduce greenhouse gas emissions.

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CLIMATE RESEARCH - STATE OF ART AND PROSPECTS

HERVÉ LE TREUT

French Academy of Sciences and Intergovernmental Panel on Climate Change. Director of the Pierre-Simon-Laplace Institute
E-mail: herve.letreut@ipsl.fr

Abstract. Milutin Milankovic's work has brought a new vision of our world that has profoundly changed the way we look at our planet. This work has essentially been carried out on scales of several thousand years, and within this context it has inspired important studies, for example to better assess the stability or instability of the climate system. But it had of course not such a strongly significant impact on studies devoted to the assessment of climate change at the scale of the coming decades or century.

However, things may change rapidly. It has become impossible to talk about climate change today with the same words and focus as in recent decades. Annual global CO₂ emissions are now close to 40 billion tons, compared to 10 billion tons in 1960. The possibilities for reducing greenhouse gas emissions still seemed wide open in the 1960s, or even at the time of the Rio Summit in 1992. But the atmospheric storage of enormous quantities of greenhouse gases, which developed within a few decades, their constant mixing by the atmospheric circulation, the absence of carbon sinks commensurate with the emissions that we cannot do without, create a new vulnerability. We often refer to the “territories” as places close to citizens, places where they live and work, places that participate in a new complexity and a new vulnerability of future climate. Anticipating the risks that arise in this rapidly changing situation creates both a new situation and a new obligation, because many of the greenhouse gas emission reduction targets that have been put forward in recent years are becoming very difficult to meet. To stay below 1.5 degrees of warming, for example, carbon neutrality would have to be achieved in less than 30 years. In the absence of sufficiently large carbon sinks, this means less than 30 years to renew 80% of the world's energy sources - all those that are carbonaceous, i.e. all those that affect traditional cars, airplanes, boats... This is a colossal task, for which there is no example today that can serve as a reference.

We are now faced with two emergencies that we must learn to reconcile. One concerns the reduction of greenhouse gas emissions. The other concerns the management of territories, the management of the people who live there, the fauna and flora that develop there - all players that must now be protected, in a preventive manner. There is nothing impossible about this conciliation. It is necessary to take advantage of what these territories already are, i.e., places where the problems posed are called urbanism, transportation infrastructures, defense of natural areas and vulnerable zones, ... But not everything is possible anymore and the "simple" vision of climate evolution that has been that of the last decades, that of a brutal rupture of the global balance of the Holocene, will no longer be sufficient to define the risks to come. It will therefore also be necessary to return to an understanding of a system marked by its complexity - a complexity that is largely interdisciplinary, and includes the mechanisms that we owe to Milankovitch.

Part III: Climate change: strategies, adaptation and mitigation

THE IMPACT OF CLIMATE CHANGES ON GROUNDWATER

ZORAN STEVANOVIĆ

*University of Belgrade – Faculty of Mining & Geology, Department of
Hydrogeology – Centre for Karst Hydrogeology, Džušina 7, 11000
Belgrade, Serbia*

E-mail: zstev_2000@yahoo.co.uk

Abstract. Groundwater is the source of drinking water for about half of the world's population. Although climate change is an inevitable natural process within the geological timeframe, its intensification caused by the anthropogenic impact raises pressure on many aquifer systems globally. The paper discusses the status of groundwater resources in the past - during the Quaternary period, the current situation, and the prospects for their future sustainable use and protection from pollution. The main emphasis is on the Mediterranean basin, where large differences of the sea level during the Messinian crisis, followed by glaciations, had caused surface and groundwater network redistribution. The forecasted global rise of the sea level could have a negative impact also on many coastal aquifers and could result in salt intrusion and salinisation of the currently tapped fresh water sources. Although Milutin Milanković's theory of climate cyclicity is beyond the scope of this kind of analyses due to time scale, his work has greatly contributed to raising the awareness of the importance of systemic observation of climate elements and forecasting their impact on human population and ecosystems.

Key words: Groundwater, Aquifer systems, Climate change, Milutin Milanković, Mediterranean basin

1. INTRODUCTION

Climate changes (CC) have never been questioned by geologists, and discussions typically revolve around their magnitude and intensity. In more than four and a half billion years since the Earth was born and more than four billion years since first rocks were created on the lithosphere surface, the climate has been changing constantly as a result of numerous factors of cosmic or local Earth's nature. For instance, during the Cretaceous period the sea level was more than 200m higher than it is now,

and the climate on most of our planet was tropical [1]. In the long history of Earth there were many exchanges of cold and warm climate, but it is curious that no glaciation took place between late Carboniferous-Permian and Oligocene - a period that lasted more than 200 million years. On the other hand, there were several glaciations during the Quaternary and Anthropogenic period phases.

Pantić and Stefanović [2] have created a list of plausible causes essential to the Earth's climate changes. They are:

- External causes including orbital variation, insolation, etc.;
- Internal causes including heat-flow in geological time;
- Complex movements inside the lithosphere such as continental drifting, volcanism, ice-caps, total water volume, shrinking of the climatic zones;
- Complex movements inside the hydrosphere and atmosphere: air and water currents, resulted from interaction of the basic causes included in the first three groups.

The climate of any given interval of a past geological time is determined as a complex interaction of the above causes [2]. Adhémar [3] was the first to indicate that climate variations could be the result of the change of shapes of the Earth's orbit. Agasiz [4] was the first to formulate a hypothesis on Anthropogene glaciations, when most of the Northern hemisphere was under a thick cover of ice. These two components constitute the basis on which Milanković started to build his concept and mathematical expression of a cyclical nature of climate changes some 80 years later [5]. Along with the work of Köppen and Wegener [6], his study "*Theorie mathématique des phénomènes thermiques produits par la radiation solaire*" became one of paleoclimatology's greatest achievements of that time [2], regardless of the fact that it was not accepted, or even understood, by many geographers and geologists. The final result of Milanković's calculations and the *Astronomic theory of climate cycles* based on three variables: eccentricity (the shape of the Earth's orbit), precession (the angle of the Earth's axis in relation to the Earth's orbital plane) and obliquity (the direction of the Earth's axis of rotation) and presented in his famous monograph „*Canon of insolation and the Ice Age problem*“ [7], resulted in further growth of a group of opponents, including some of well-known names in Quaternary and glacial geology (e.g. Albrecht Penck, [8]; Richard Foster Flint, [9]).

Aware of the fact that some other terrestrial factors also influence the effects and intensity of climate changes (see causes 2-4 listed above, by Pantić and Stefanović [2]), in close cooperation with geologists Milutin Milanković looked for evidence and additional facts which would confirm his theory [10]. Eventually, his findings were proven without any doubt by the results of a large international project CLIMAP undertaken in 1971-1976, when drilling of the Indian Ocean floor and sedimentary analyses of obtained cores took place along with extensive paleomagnetic, paleontological and geochemical investigations [11].

Nowadays, the topic of climate changes is actualised and commonly considers anthropogenic impacts on climate as well as, consequently, natural resources and biodiversity at the scale of hundreds or a thousand years [12]. This scale is considerably different than the one Milanković was able to use in his calculations, i.e. 10,000 or 5,000 years. Although, due to time scale, Milanković's theory of climate cyclicity is generally beyond the scope of many current analyses [13] which consider the actual anthropogenic impact (i.e. scale of centuries), his work has greatly contributed to raising the awareness of importance of climate elements' systematic observation and forecasting their impact on human population and ecosystems.

Groundwater is one of the most important and precise natural resources. Climate changes have greatly influenced this resource, and their consequences – such as prolonged droughts with reduced aquifers' recharge, desertification and salt-water intrusion – put great pressure on groundwater and are a risk for its further sustainable use.

2. GROUNDWATER – THE PAST

Our analysis of the status of groundwater does not consider far geological past, but only the last several million years (the period from Late Miocene to Anthropocene). The focus is on the entire Mediterranean basin as a region of a very dynamic geological past and present.

One of the main geologically critical periods was between 6 and 5.3 million years ago (Ma). The Messinian salinity crisis (MSC) was a period when the previously large Tethys Ocean became considerably reduced, decomposed and isolated from the other oceans that functioned as a large salty lake in the Mediterranean depression.

The MSC was an ecological crisis caused by a powerful combination of geodynamic and climatic drivers; it had a great impact on the subsequent geological history of the Mediterranean basin as well as on the salinity of global oceans [14]. This lake used to be significantly smaller, and the connection - via the Gibraltar strait - between the Mediterranean Sea and the Atlantic Ocean was broken (Fig. 1). The sea level was lowered down by more than 1,500 m in about 100,000 years and thick evaporitic rocks and salt deposits were formed in the basin in the absence of inflow of ocean's water. Since the 1990's, the MCS has been considered by the scientific community a major period of development of a surface waters network, especially of an underground system of karst conduits at great depth and below the present sea level [15].

For instance, during MSC, most of today's islands in the Adriatic basin (Croatia) were connected to the continent, while mountains built dominantly from carbonate rocks were exposed to intensive karstification and deepening of the groundwater table. The lowering of the base level simultaneously caused the lowering of springs and conduit systems. Many deep canyons were incised, transferring river waters to a "new" and much deeper erosional base. One of such submarine canyons, more than 300m deep, can be found in Cassidaigne near Marseille [16]. This was also one of the important phases of the uplifting and creation of the Dinaric mountains range, the area which is often called "classic karst" [17,18,19]. The re-modification of relief and hydrographic / hydrogeological network also took place in other chains of the Alpine orogenic belt (Apennines, Pyrenees, Atlas, Hellenides).

At the beginning of Pliocene, around 5.33 Ma, the opening of the strait of Gibraltar by way of erosion caused a sudden inflow via gigantic waterfall. Bakalowicz [15] states that flood filled up the Mediterranean basin in a few decades, lowering the global ocean by some 15 m.

The water level and poorly permeable clay deposits caused many previously open joints and cavities in karst aquifers to be filled; groundwater circulation was disrupted and often redirected to other sub-basins.

The rising of the base level resulted in the flooding of at least the lower part of the karst conduit system and the overflow of the aquifer at higher

elevation, potentially rejuvenating abandoned karst structures [15]. Deep karstification resulted in the fact that today more than 90% of all the known submarine springs in the world are located in the Mediterranean basin [20].

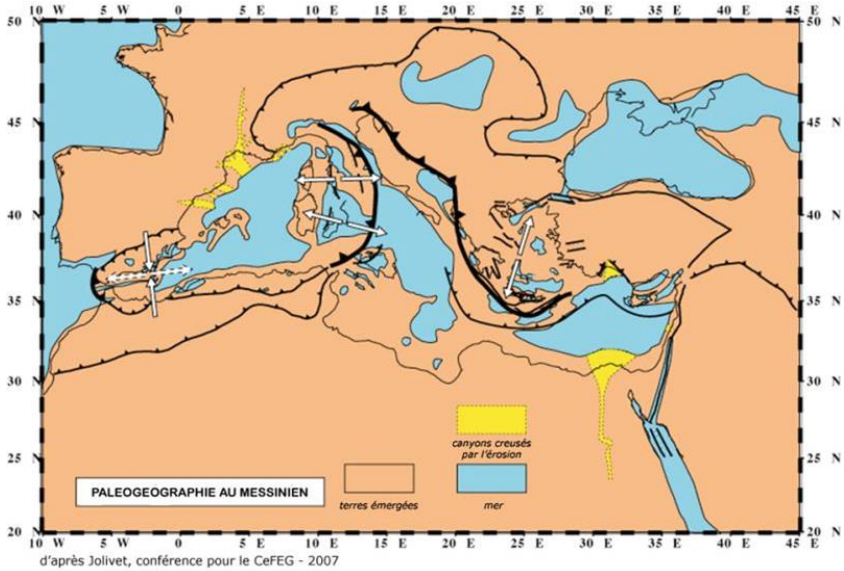


Figure 1: Sketch map of the Mediterranean basin at the time of the Messinian crisis. The Gibraltar strait between the Mediterranean Sea and the Atlantic Ocean was closed and the sea level was some 1,500m lower, according to Jolivet et al. [21].

Another critical phase for groundwater distribution and circulation took place during the Pleistocene and glacial phases. A very thick ice cover along the entire Europe caused water balance to be completely modified. Reduced inflow of fresh waters into the Mediterranean basin caused another deepening of the sea level and reduction of the volume of the sea water pool. In the last two million years, the mean sea level reached positions as low as 130m below the level which was present during glacial periods, and as high as ~ +6m and possibly +13-15m during interglacial periods (Fig. 2; Benjamin et al. [22]).

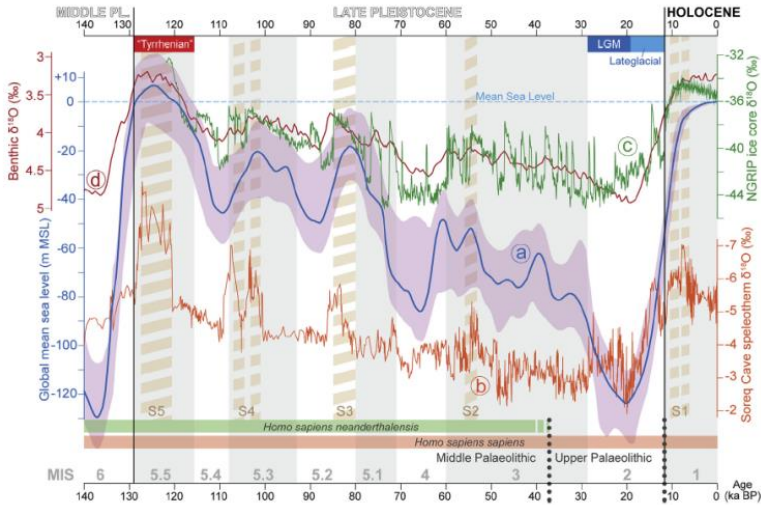


Figure 2: Comparison between the past global mean sea level and paleoclimatic, paleoenvironmental and archaeological data for the Mediterranean basin based on multidisciplinary research. Period from the Middle Pleistocene to present (source: Benjamin et al. [22])

In the Adriatic basin, during the period of maximal glaciations the seashore line was moved by one to tens of kilometres to the west. Figure 3 shows a topographic-nautical map of the exemplary area of the Bay of Boka Kotorska. The isobath line of 100m and measured depths of the seafloor indicate that Boka Bay was in fact a dry depression without any sea water during all four main glacial periods (Günz, Mindel, Riss, Würm). The tracers of glaciers transported the material, and moraines are evidenced at Orjen Mt. high above the Bay. The direction of groundwater flow was similar or keeping the general course of these glaciers or paleo streams. The springs, where most of the karst aquifers had drained during the interglacial stadiums (Fig. 3), are now at the sea level or just a few metres above it (Gurdić, Škurda, Tabačina near Kotor, Ljuta orahovačka, Risanska spila, Morinj), or are functioning as submarine springs (Sopot).

The confirmation of such morphological and hydrological development came as a result of multibeam bathymetry combined with seismic reflection images [23]. They showed a maximum depth of 67m in the narrowest part of the Verige passage (Fig.3) while the observed morphologies showed steep upper slopes and flat sub-basin central sectors lying at depths ranging from 35 to 45m. Seafloor morphology is the result

of interaction at different timescales of climate, water circulation, sea level changes, erosion, sedimentation and tectonics constrained by the geological and structural setting of the area [23]. The deeply incised valleys are related to past seafloor falls triggered by strong earthquakes, while delta fans have resulted from sedimentation of strong bottom streams. These pathways were reconstructed by the author of this paper and shown in Figure 3. Some streams just followed the path of the valleys that were incised in the pre-Quaternary period (pre-glacial), while others originated from karstic springs.

The sea level was progressively raised to the present position during the post-glacial period of the last 10,000 years, and the surface waters network and incised valleys inside the Boka depression were fully submerged. Surface water network in the surrounding hilly-mountain area (Lovćen, Orjen) was degraded, while recharge of aquifer systems from heavy rainfall intensified. The processes of weathering of epikarst, the creation of sedimentary cover, and intensive karstification with fast deepening of the water table led to the development of thick and highly karstified rocks and rich aquifer systems.

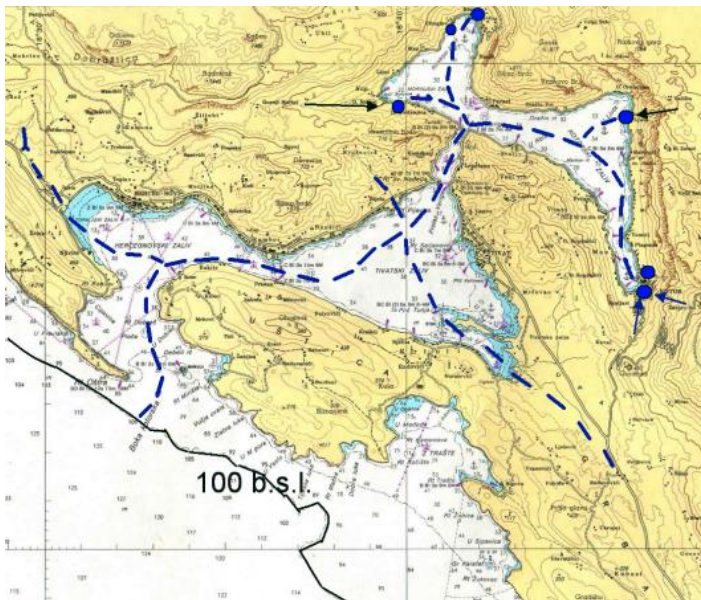


Figure 3: Topographic-nautical map of Boka Kotorska. Blue dots show locations of today's main active springs and vruljas (submarine springs); arrows show groundwater flow directions; black line is the isobath line of 100m below sea level (b.s.l.); dash lines show the reconstructed riverbed of paleoriver Boka

and its tributaries based on actual deepest depths to the seafloor (Map source - Website: Best of Boka, modified [24])

3. GROUNDWATER – THE PRESENT

Groundwater is our planet's essential resource. Currently, between 1.5 billion and 2.5 billion people depend solely on groundwater to satisfy their daily need for potable water [25,26]. Approximately 38% of the crops in the world are irrigated by use of groundwater [27]. Irrigation is the main consumer of groundwater and in many arid parts of the world no crops can be grown without pumping groundwater [28]. Therefore, 70% of the total amount of extracted groundwater is utilised for irrigation, 21% for drinking water supply, while the remaining 9% is abstracted for industrial or mining purposes [29,30].

Groundwater is used the most in Asia (70%). Global population growth and climate change are the main threats to freshwater resources (Fig. 4). These two factors provide a negative synergy and many countries or regions are already facing water shortage and significant depletion of their water reserves (China, India, parts of USA, Arabian Peninsula, northern Africa). Currently, 18 countries that host half of the world's population are over-pumping their aquifers [31]. Such a situation is likely to continue and forecasts are even worse concerning the arid part of our planet [32,28].

A series of reports issued by the Intergovernmental Panel on Climate Change (IPCC) concluded that the climate of our planet is changing [13]. The most important impacts of climate change on the world's fresh water supplies will be those caused by increased temperatures, changed precipitation and shifts in the historic hydrologic cycle. Increased air temperatures changed the regime of precipitation and humidity, strongly impacting the world's fresh water supply [33]. The fourth IPCC report [13] estimated a global pattern of contrasting changes in rainfall to occur between the present and the end of the 21st century, with a decrease in rainfall, compared to the 1980-2000 averages, that could exceed 20% in arid and semi-arid zones which are already vulnerable to reduced recharge of water resources. This change will have an impact on land use activities, which in turn will exert pressure on water resources.

CC can also alter water consumption, with demand increasing during dry, warm periods and decreasing during periods that are cool and wet [34]. Depletion of groundwater resources is likely to continue, and the impact of CC and reduced recharge during extended droughts will not affect only the quantity but also the quality of groundwater [35]. The sea level increase will further stimulate salt-water intrusion and reduce the quality of many coastal aquifers.

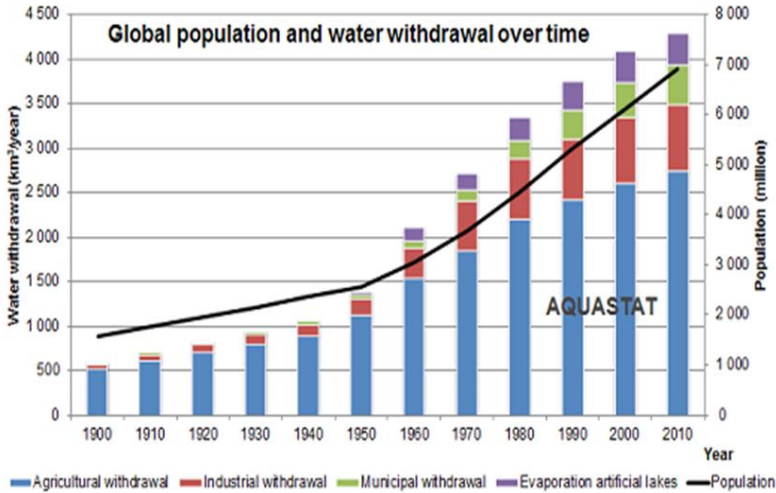


Figure 4: Simultaneous growth of the global population and water withdrawal in the period 1900-2010 (according to FAO Aquastat [36])

Due to the presence of rich karst aquifers, moderate climate with well-balanced rainfalls, and intensive water balance, the Mediterranean basin is not that affected [37]. However, there is a big contrast in water resources availability between the northern parts of Europe and southern parts of North Africa and the Near East.

In the Mediterranean region, the main aquifer systems are located in thick alluvial fans that follow major rivers and highly karstified carbonate rocks. The percentage of participation of groundwater in the public supply varies from one country to the next but is generally over 50%. A large portion thereof represents consumption of groundwater from karst aquifers, the highest being in Montenegro, where it exceeds 80%. Many large settlements, including six European capital cities of this region (Vienna, Rome, Sarajevo, Podgorica, Tirana, Skopje) base their water supply on tapped karst springs. Most cities along the shores of the Adriatic and Ionian seas, as well as many settlements on the islands, were founded

near large springs and their development is the result of the presence of these springs. For instance, cities such as Rijeka, Split, Dubrovnik and Kotor became important naval and (later) tourist centres thanks to these large water sources. Data showing water availability per capita are more illustrative. In an average hydrological year, each inhabitant of Montenegro has 21,395 m³ of water available, but utilises just 1.18 % of it. In Bosnia and Herzegovina the utilisation rate is even lower, below 1%. Citizens of Croatia and Albania use less than 5% of water that is available to them per capita [36].

However, the situation with water availability is not favourable everywhere, and over-extraction is present in Lebanon, Morocco and Syria. Although some springs of Boka Kotorska, Montenegro belong to the group of the world’s most powerful, due to their maximal discharge during the recession periods in summer and early autumn months they tend to dry out or drain small amounts of water below the sea level. As such, the Sopot spring near Risan (Fig. 5) can discharge more than 100 m³/s during maximal floods, but for most of the year it functions as a submarine spring. The highest discharge is a result of fast prolongation and short residence time for the rainfall water infiltrated at the Orjen Mountain and “Stone Sea” area, where more than 300 vertical shafts were registered within the area covering only 8 km², with depth of 200-350 m [38].

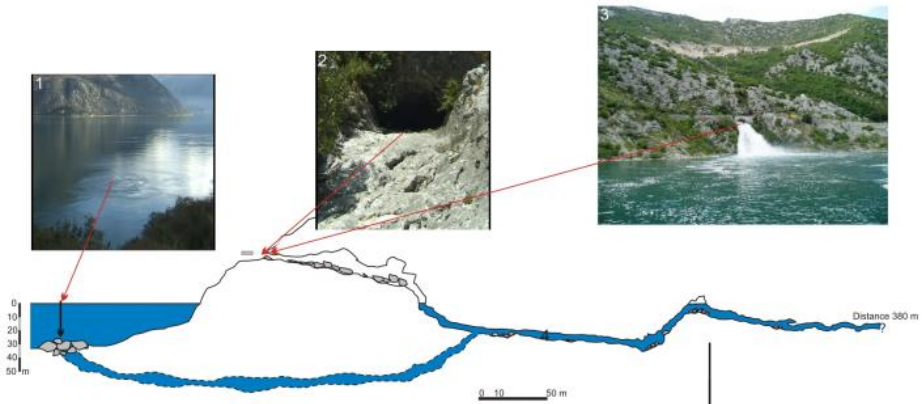


Figure 5: Photos and section of the Sopot spring near Risan in Boka Kotorska, Montenegro. During maximal floods it is one of the world’s largest (3), but with a dry orifice (2) and submarine discharge (1) during summer. (According to Milanović S., [39]; reprinted from Stevanović, 2010, Elsevier copyright [40])

Engineers and water managers are thus facing many problems in their attempts to ensure water provision: due to the unstable regime of karstic springs, the main challenge for most of the waterworks is to overcome water shortage during recession periods, which coincide with summer and early autumn months when consumption is at its highest [32]. Several successfully completed projects based on utilisation of groundwater from considerable storage in the deeper parts of aquifers provide a new prospect for the development of aquifer systems in many locations, as was done with the sources of Lez (Montpellier, France) and Bolje Sestre (the Montenegrin coast [40]).

4. GROUNDWATER – THE FUTURE

“The past is the key to the future”. This well-known sentence can be accordingly applied to many current attempts of the scientists to forecast impacts of climate changes on the environment and natural resources. And this is also why many of them have Milanković’s theory and its findings as their starting points.

Many projects conducted in the past two decades aimed to forecast the magnitude and effects of climate changes on groundwater in different types of aquifers [41,42,43]. The forecasting period usually extends up to the end of the 21st century. These projects often use greenhouse gas emission scenarios developed by the IPCC [13] and create climate projections by manipulating Global Climate Models (GCM). By correlating GCM downscaled climate data to the basin scale of a specific grid, and coupling them with observed historical data of a spring’s discharge or water table fluctuations, it is possible to establish a cross-correlation between climate elements and the groundwater regime. The outputs of these coupled models are numerical and include the aquifer’s response to predicted climate conditions [44,45]. Hartmann *et al.* [46] developed a large-scale simulation model to assess karstic groundwater recharge over Europe and the Mediterranean, which can also be used to forecast further climate and hydrology situations. Some recent studies are also aiming to assess aquifers’ behaviour and their intrinsic vulnerability or resilience to variable climate elements and primary rainfall, which happens to be the main recharge component [47].

Climate simulations suggest that, in the next 90 years, Mediterranean regions will be exposed to higher temperatures and lower amounts of precipitation [13]. Further inland, the predicted changed climate elements include an additional reduction of days with snow and intensive rainfall in winter, and extended droughts in summer-autumn months.

The example of forecasted average discharges for low-water seasons (summer months) until the end of 21st century is presented in Figure 6. The tested Mlava spring in the Carpathian karst of Eastern Serbia is the largest in the entire region and its discharge has been continually observed the longest (since 1969). The diagram shows real measured data up to 2010 and data forecasted by use of bias corrected GCM and a stochastic model created for the rest of the concerned period. Significant depletion trend is evidenced [42].

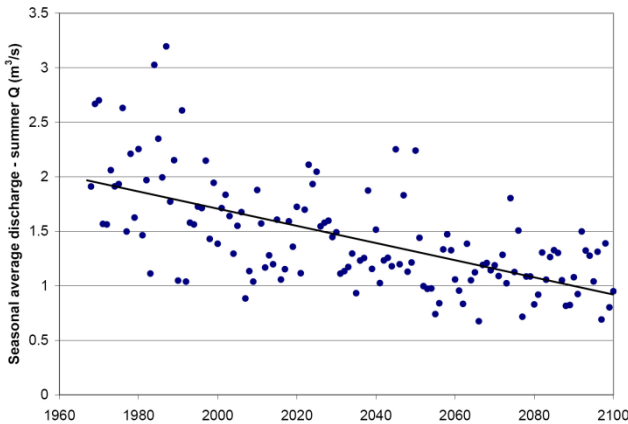


Figure 6: Seasonal (summer period) average discharges of Mlava spring and the trend line until the end of 21st century (Stevanović et al. [42])

Many coastal springs in the Mediterranean basin are in danger from further sea level rise as a consequence of climate changes. The situation is the same with Almyros, the largest spring on the island of Crete in Greece, which had supplied Heraklion with potable water for many centuries. The spring issues at the elevation of 5m asl (Fig. 7), but the deeper part of the aquifer is under a strong influence of salt intrusion.

The spring discharge varies from 3.3 to 30m³/s and the problem with salinity starts with the discharge lower than app. 15m³/s (during minimal yields, concentration of the Cl ion reaches 6 g/l). The concrete dam,

constructed at the discharge point to increase the freshwater level, only partly mitigates the problematic brackish flux [48].



Figure 7: Almyros spring (Heraklion, Creta, Greece) during a period of low water when concentration of Cl ion raises.

The GEF/UN Environment project MedPartnership completed in 2015 produced amongst others an assessment of coastal aquifers and related coastal ecosystems in all Southern and Eastern Mediterranean and Adriatic countries [49]. The project provided conclusive evidence that:

- Climate change and variability will increasingly affect Mediterranean coasts and the livelihoods of ever-growing coastal populations, compounding all other issues of transboundary concern, with particularly severe impacts in identified hot spots;
- The critical role played by coastal aquifers within the context of the coastal zone including the shallow marine environment is fully confirmed.

From the time immemorial the city of Kotor in Boka Kotorska Bay, Montenegro has been using groundwater from Gurdić and Škurda, two springs located just outside the city fortress walls. The former is currently issuing at 0.0 +/- few cm. asl. Consequently, fresh water can be tapped during periods of flood, while during the summer spring water becomes brackish and then more and more salty. With further rising of the sea level in the coming centuries, this spring will no longer be usable. However, the recently completed project of tapping the spring Bolje sestre in the Skadar basin and distributing its water to the entire Montenegrin Coast has provided an adequate alternative [50].

Millenia will be needed for some other springs along the Mediterranean coast to be submerged by sea water, as they are located a few metres above the sea level. With this sort of time-scale, we are approaching the scale

from Milanković's theory of climate cyclicity, or change of climate under the influence of a combination of natural and cosmogenic factors on one side, and anthropogenic impact on another. However, if the anthropogenic impact remains dominant, most climatologists agree that the sea level raise could reach a magnitude of 1m/1000 years. For example, with such a time scale, the main water source for the city of Dubrovnik – Ombla – will be under sea water in less than 2,500 years.

Some other coastal aquifers will also gradually become more brackish. The Bojana/Buna River issues from Skadar Lake at the elevation of 6m a.s.l. With a very small gradient, this river flows towards the Adriatic Sea, receiving also a certain amount of water from its large tributary Drin (Drim) River. With the above indicated magnitude of the sea level raise, the large alluvial delta of Bojana will be transformed into a salty marsh in about 6,000 years (Fig. 8). In this case, the current groundwater source Lisna-Bori near Fraskanjel, used to supply the city of Ulcinj, will be abandoned, while many vruljas (sublacustrine springs) along the banks of the Skadar Lake will also be affected by salty and brackish water inflow.



Figure 8: Skadar Lake and Bojana River valley and confluence to the Adriatic Sea. The shaded area has altitudes 0-6m and is under threat of being submerged (source: Google Earth copyright)

5. CONCLUSIONS

This paper took the reader through a time-tunnel which started about 6 million years ago, crossed the present environment and ended somewhere

in the very probable future. From the geological point of view, this future is very close. The Mediterranean basin and the Montenegrin coast, in particular, have been chosen as test areas. The entire region has a very dynamic geological history and is still exposed, in certain parts, to active and dramatic geological events such as volcanic eruptions, earthquakes and floods.

The focus of this analysis is on groundwater and its evolution. During the 20th century, air temperature in the Mediterranean basin was observed to have risen by 1.4 °C to 4 °C depending on the sub-region. As such, the countries of the Mediterranean are already witnessing the impacts of climate variability. Most of the cities of the region use groundwater for potable water supply, but many of them are facing shortage of water during summer months due to very unstable and dynamic regime of karst aquifers, which are the principal utilised resource. According to IPCC report, by the end of the century the rise in temperatures is expected to be between 2°C and 4°C for the medium-low emissions scenario (RCP 4.5). At the same time, overall rainfall is also likely to decrease as high as 20% less than the current mean precipitation.

Other important water management problems are high aquifer vulnerability to pollution and salinisation - especially along the coast and on the islands. However, due to intensive water balance, sufficient rainfall and good absorption capacity of karst aquifers when receiving the rain, it is still possible in many places to intervene and artificially adapt the groundwater regime. Several such successful projects, including the most recent one which included tapping the Bolje sestre spring to supply the entire Montenegrin coast with water, may mitigate the water situation in decades and even centuries to come. Therefore, sustainability in water exploitation and environment protection should remain primary goals of water managers and decision makers in the entire Mediterranean region.

Milanković's theory of climate cyclicity has a much larger time scale than those that applied to centuries, and does not include terrestrial (geological) factors or the anthropogenic impact which is currently highly influencing our planet's climate. However, most of our analyses of the impact of climate change on water resources are stemming from his findings, and they must be taken in consideration when forecasting for extended periods of thousands of years. Anticipating climate changes and assessing their impact on water resources is essential for safeguarding the future water

supply and designing a sustainable water management system which would also enable protection of dependant eco-systems.

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IMPACT OF CLIMATE CHANGE ON FORESTS

**RATKO RISTIĆ, BORIS RADIĆ, SINIŠA POLOVINA,
IVAN MALUŠEVIĆ, VUKAŠIN MILČANOVIĆ**

University of Belgrade, Faculty of Forestry
E-mail: ratko.ristic@sfb.bg.ac.rs

Extended abstract

Humanity is a dominant global influence on life on earth, and has caused natural terrestrial, freshwater and marine ecosystems to decline. Global forest area is now approximately 68% of the estimated pre-industrial level, while 27% of the global forest resources is extremely endangered. “Virgin” forests were reduced by 919 000 km², between 2000 and 2013, both in developed and developing countries. Humans are responsible for warming of approximately 1°C by 2017 relative to pre-industrial levels. The climate change in Southeastern Europe (SEE) and forecasts for the period 2071-2100 have a huge impact on the present and future planning in forestry and watershed management, due to the observed trends: the increment of mean annual air temperature from 2.4-4.5°C until the end of the XXI century; redistribution of annual precipitation, with much more precipitation in the spring-summer period, during short, intensive rain events; a decrease of annual precipitation and soil moisture of 10-20%, with extreme consequences: drying and disappearance of climatic forests in huge areas of hilly-mountainous regions.

According to the Serbian National Forest Inventory, forests in Serbia cover 2 252 400 ha (29,1 % of the total area of the country). The average volume in state-owned forests is 184 m³/ha, and the annual volume increment amounts to 4.5 m³/ha (2,4%). The average volume in privately-owned forests is 133 m³/ha and the annual volume increment is 3,5 m³/ha (2,6%). Private forests cover some 1 058 400 ha, or approximately 47% of Serbia’s total forest area. There are about 500 000 private forest owners, who on average each possess about 2 ha of forests, often divided into six or seven parcels, which are often not spatially connected.

Fires are a significant factor of deforestation in Serbia, with 400 events in the period 2012-2018, on a total area over 8 500 hectares. In 19 cases the cause was thunder, in 178 the fires were man-induced and in 203 cases

the causes were unknown (likely man-induced). The extreme droughts damaged sensitive relationships between spruce and root pathogens, after which there was a collapse of the trees and weakening of their resistance. The total volume of spruce trees logged because of the dieback (2012-2016) in the Park of Nature „Golija” amounted to 68 000 m³. Drought in summer 2014. caused defoliation and drying of 2.1% conifer trees in Serbia. Fragmentation of forests is followed by habitat loss that seriously endangers forest wildlife. Altered radiation, wind, water, and nutrient regimes create new habitat conditions, inducing tree mortality in fragments and strongly influence forest dynamics and structure. An illustrative example of forest fragmentation is the destruction of 26 ha of native mature forest in the ski resort “Stara planina”, when two fragments were created, endangering two local endemic plant species - *Campanula calycialata* (found only in the proximity of), and *Senecio pancici* (steno endemic of the Central Balkans), and more than 10 species from IUCN Red list of threatened species. The estimated volumes of illegally cut wood in Serbian public forests are between 10 000 and 32 000 m³ per year, while the total amount of illegally cut wood in private forests is estimated at about 500 000 m³. Illegal logging is also very pronounced in southern Serbian municipalities, near administrative border to Serbian province Kosovo and Metohija.

Torrential floods are the most frequent natural catastrophic events in the SEE region, causing loss of human lives and huge material damage, in both urban and rural areas. In Serbia alone, torrential floods have caused death of more than 130 people in the last 64 years and material damage estimated at more than 12 billion €. The soil and vegetation cover directly affect the intensity of the surface runoff by creating "losses" of precipitation through the processes of interception, evaporation, transpiration, and infiltration. Clearcutting and the removal of forest vegetation influence the water balance by affecting evapotranspiration and possibly snow accumulation and melting. The risk of erosion processes, fast surface runoff, and torrential floods can be significantly decreased by land-use changes (afforestation of bare land, reclamation of degraded forests, meadows and pastures, silt filtering strips, contour farming, and terracing) in order to reduce erosive material production and meliorate water infiltration and water storage capacity of the soil.

In accordance with the National Renewable Energy Action Plan of the Republic of Serbia around 120 Small Hydro-power Plants (SHPP) have

been built in Serbia, of Derivation Type (SHPP-DT), with pipelines in length of 2–5 km. Additionally, 736 SHPP-DTs are planned for construction in mountainous regions of Serbia, mainly in protected natural areas (National Parks, Nature Parks, Special Nature Reserves). Serbia is the poorest country in the Balkans when it comes to indigenous surface waters (annual specific runoff $q = 5,7 \text{ l s}^{-1} \text{ km}^{-2}$). The implementation of this has led to the endangerment or even disappearance of endemic and protected fish species, fragmentation of the most valuable aquatic habitats, fragmentation of forests (due to the construction of access roads and derivative pipelines), endangered water supply of local communities and intensive erosion along access roads. All the planned SHPPs would provide only 2–3,5 % of the annual energy needs of Serbia, but that would mean total devastation of most of the quality watercourses and forest stands in the mountain regions of Serbia.

According to the currently prevailing Spatial Plan of RS it is planned that the degree of afforestation by 2050. should reach 41,4% (36 581.45 km²), meaning that the surface area under forests would increase by 10 868.40 km² (1 086 840 ha). Afforestation of such a great area is a major technical and social challenge which can be addressed through staged performance of relevant activities, in line with appropriated financial, material and technical capacities of Serbia. Therefore, it is proposed in the first stage, in the period 2021-2030, according to the United Nations „Sustainable Development Agenda 2030“, to implement the objectives from the „Strategy of Water Management in the territory of the Republic of Serbia“ and the „Regional Spatial Plan of AP Vojvodina until 2020“, envisaging afforestation of 100 000 ha bare land and degraded area south of the Sava and the Danube rivers, as establishing 171 831 ha of forests in AP Vojvodina, primarily in form of multi-layered protective windbreaks. Practically, starting with 2021, this would imply annual afforestation of 27 183 ha, of which 10 000 ha in hilly and mountainous regions south of the Sava and the Danube rivers and 17 183 ha in the flatlands of AP Vojvodina, ending with 2030. Taking into consideration that the average costs of afforestation per 1 ha in hilly-mountainous regions is EUR 2200 (using container seedlings, with planting density of 1500 seedlings per hectare) and the relevant costs in flatlands in EUR 1500, the total amount is EUR 477 746 500 or EUR 47 774 650 annually. In the period 2021–2030 this would mean planting 407 746 500 seedlings or 40 774 650 seedlings annually. Through the implementation of activities of the first stage in the period from 2021 to 2030, the degree of afforestation of Serbia

would be increased from 29.1% (25 713.05 km²) to 32.18% (28 431.36 km²). Achieving the degree of afforestation of 41.4% (36 581.45 km²) would require afforestation of additional 815 009 ha in the period from 2031 to 2050, with cost estimates of EUR 1793 billion.

Climate change and natural hazards cannot be prevented, but a better understanding of the processes and scientific methodologies for their prediction can help mitigate their impacts. Wood processing industry practices and products must be raised in order to achieve higher ratio of final products when compared to raw wood, maximizing financial benefits and decreasing the volume of exports of semi-final products, which would provide a more rational utilization of the growing stock. Forest management from the aspects of mitigation of climate change effects and natural hazards prevention should be complementary with other demands such as environmental protection, sustainable soil usage, drinking water supply, local economic development and sustained biodiversity. The restoration of eroded and deforested watersheds is one of the key activities in the process of mitigation and adaptation to the effects of climate change, as well as the reduction of disaster risk. It involves biotechnical works on slopes and technical works in the channel network, coordinated within a precisely defined administrative and spatial framework. Cooperation and overcoming of conflicts between the sectors of water resources management, forestry, agriculture, energetic, environmental protection and local economic development are indispensable at the following levels: policy, spatial planning, practice, investments and education. It is very important to connect these measures with the process of mitigation and adaptation to climate change in accordance with the “RIO” Conventions of UN.

Key words: Forest ecosystems, Climate change, Afforestation, Erosion control, Watershed management.

BENEFITS OF GREEN INFRASTRUCTURE FOR CLIMATE-RESILIENT FLOOD MITIGATION IN RURAL WATERSHEDS

JASNA PLAVŠIĆ¹ and RANKO PUDAR^{1,2}

¹*University of Belgrade – Faculty of Civil Engineering, P.O. Box 42,
11120 Belgrade, Serbia*

E-mail: jplavsic@grf.bg.ac.rs

²*Pudar Mitigation Consulting, Inc., P.O. Box 680725, Marietta, GA
30068, USA*

E-mail: ranko_pudar@pudarconsulting.com or rpudar@grf.bg.ac.rs

Extended Abstract

Adverse effects of climate change and depleting natural resources, along with many socio-economic issues, are the greatest global challenges today. One of the facets of this global problem is that there is an increasing need for improved protection from natural hazards, and specifically from flood hazards. Reducing flood risk in the past has been typically based on structural flood mitigation measures, the most of which could be qualified as the “grey infrastructure” (e.g. culverts, concrete-lined river channels and/or levees). Besides being demanding in terms of maintenance costs, grey infrastructure can lead to degradation of local and regional ecosystem functions and services [1].

Nowadays, there is a growing attention for so-called nature-based solutions or “green infrastructure” that could be used for mitigation of flood risks [2]. Riverine floodplains, natural detentions, reclaimed wetlands, etc. are examples of green measures for flood risk mitigation. These measures can be less expensive than grey infrastructure (e.g. [3]) and can provide an array of co-benefits (environmental, social, economic) [4]. Green measures have been intensely considered lately at small scale for urban areas, but the flood mitigation solutions in rural areas may span over watershed or regional scale and include larger scale nature-based solutions, or some combination of the green and grey infrastructure approach. Selecting the most effective strategy for flood risk management or for adaptation to climate change requires quantitative evaluation of different flood mitigation measures and scenarios by means of the flood risk assessment.

This paper presents a quantitative evaluation of different flood mitigation scenarios (grey, green, and combined green and grey) for the small rural watershed of the Tamnava River in Serbia (Figure 1), which has a rich history of floods, the most catastrophic one being the May 2014 flood. The existing flood mitigation measures in this basin include the levees in urban centers, designed for the 50-year or 100-year flood, and low-level levees for the 25-year flood in some agricultural areas. The levees, as the traditional structural measures, are considered here as the grey measures. The grey flood mitigation scenario includes elevating the existing levees to protect against the 100-year floods, and a diversion canal from the Gračica River to the Ub River. On the other hand, three detention basins in upstream sectors of these three rivers are proposed as the green flood mitigation scenario. Additionally, the combined green-grey scenario is also considered.

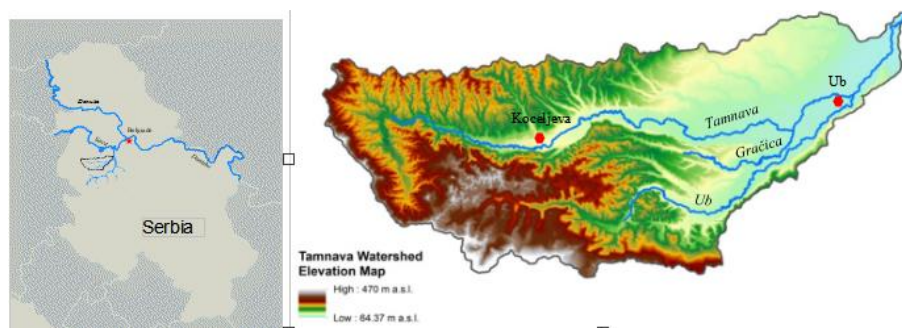


Figure 1: The Tamnava River basin (adapted from [5]).

Flood risk assessment is a well established procedure, consisting of several steps. The first step is the hazard assessment, in which hydrologic and hydrodynamic models are employed to estimate the effects of floods (flooding depths, water velocities and flooding extents) of various probabilities of occurrence for each mitigation scenario. The second step is to identify the assets in the flooded areas (e.g. buildings, infrastructure, population affected). The choice of the asset categories for which the damages are calculated can significantly affect the results and it is therefore important to choose the categories for which the potential losses are the greatest. Our choice included the categories which were the most affected ones during the 2014 flood. The following categories of assets are considered: buildings (residential and public), building contents and equipment, agricultural crops, and population emergency displacement

and relocation. Our study involves a micro-scale flood risk model in which the assets are represented in high detail. The damages are evaluated by means of so-called depth-damage curves for buildings and their contents, and using unit costs for other asset categories. Finally, our micro-scale damage model was validated against the official post-disaster loss estimates in 2014.

The estimated damages allow establishing the probability distribution of the damages for each scenario and finding corresponding expected annual damage. From this, we can find the expected value of the benefits from each flood mitigation scenario as the reduction of losses in comparison to the existing setup. The long-term benefits over a planning horizon of e.g. 30 or 50 years can also be considered.

In the Tamnava basin, all scenarios provide reduction of damages, but the green and green-grey scenarios lead to greater reduction (greater benefit) than the grey scenario (Figure 2). The greatest benefits arise from reducing damages to agriculture. This is an important conclusion because the agricultural areas are usually considered less valuable than urban areas, but in a predominantly agricultural river basin, this is an important factor. The benefits from the green measures are the greatest for the river sectors in the agricultural areas, where the grey measures do not provide any benefit because these are the sectors without the levees. The combined green-grey scenario is only marginally better than the green one because of the extra diversion channel, and shows that levee heightening is not beneficial if combined with the detention basins, which can significantly reduce the downstream floods.

To conclude, in rural and agricultural settings, losses to agriculture are an important component in flood risk assessment and selection of an optimal flood mitigation scenario. In this case study, the levees as the grey measure proved inferior to the green detention basins aimed at significant peak flow reduction; they merely provide local protection, while the green scenario affects the whole downstream area. Also, applying the micro-scale assessment reduces uncertainty that is so generally inherent in this type of studies.

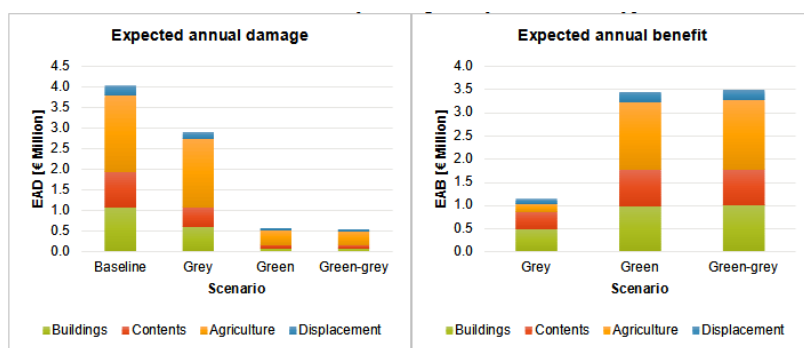


Figure 2: Comparison of expected annual damages (left) and benefits (right) for the three considered flood mitigation scenarios.

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PHYSICAL MODELS OF SPRING DISCHARGE

ATTILA KOVÁCS^{1,2}

¹*University of Miskolc, Hungary*

²*Budapest University of Technology and Economics, Hungary*

Abstract. Hydrographs are time series of spring discharge. Hydrograph analytical methods include time series analysis and single event analysis. While time series analytical methods are usually used for forecasting, data completion, and correlation analysis, single event methods based on analytical solutions can provide quantitative information on hydraulic and geometric characteristics of karst systems.

Novel single event hydrograph analytical methods used in this study establish links between conduit geometry, aquifer properties and hydrograph recession coefficients, and describe the spatial and temporal variations of spring discharge. A combination of time-series analytical methods with single-event techniques provides an efficient tool for spring discharge forecasting.

The proposed methods are demonstrated through the application of field data. Two test sites were studied through systematic spring discharge monitoring and hydrograph analysis.

At the Szinva catchment, Bükk Mountains, Hungary, hydrograph analysis of several flood peaks and master recession curves of data series were undertaken to determine aquifer characteristics, conduit spacing and hydraulic behaviour. The results of hydrograph analysis were verified through field observations. The analysis revealed the long-term hydrodynamic behaviour of the system, and changes of flow scale throughout the recession process.

At the Bukovica catchment, Durmitor Area, Montenegro, a combined stochastic-analytical modelling of discharge hydrographs was introduced. Regression functions between rainfall and peak discharge were established using historical data. Baseflow recession was described using a double-component exponential model, where parameter fitting was performed on Master Recession Curves. Rainfall time series from six

selected Regional Climate Model scenarios were applied in order to predict future discharge time series. The applied method is suitable for simulating the temporal distribution and magnitude of discharge peaks and also for baseflow recession.

INTERMITTENT RIVERS - A MODEL FOR STUDYING CLIMATE CHANGES AND ITS IMPACT ON BIODIVERSITY

VLADIMIR PEŠIĆ¹ and ANA SAVIĆ²

¹*Department of Biology, University of Montenegro, Cetinjski put b.b.,
81000 Podgorica, Montenegro;
E-mail: vladopesic@gmail.com*

²*Department of Biology and Ecology, Faculty of Sciences and
Mathematics, University of Niš, Višegradska 33, 18 000 Niš,
Serbia; E-mail: anka@pmf.ni.ac.rs*

Abstract. Intermittent rivers are defined as the rivers that periodically cease to flow. In most environmental studies this term refers to all temporary, ephemeral, seasonal, and episodic streams and rivers in defined channels. In the last decade, research on Intermittent rivers has become a "hot" topic in the field of fundamental ecology, attracting a large number of scientific teams over Europe and the world, and a significant number of international projects (e.g., SMIRES – COST Action CA15113) and managers and stakeholders interested in better recognition of these habitats.

Most of these studies emphasized that the extent of intermittent rivers in the global river network is increasing, presumably due to climate change. Intermittent rivers make up more than half of the global river network, especially in arid and semiarid regions, such as the Mediterranean and sub-Mediterranean regions where these rivers dominate the local hydrographic network.

However, most of these habitats, both in Serbia and Montenegro, have been neglected in regular monitoring programs. None of the surface-water gauging stations in Serbia was placed on such watercourses, so there are virtually no data on whether the dry periods show a tendency of increase as can be hypothesized. The both, the flowing and non-flowing phase of intermittent rivers are biogeochemically and ecologically active and

provide essential ecosystem services, for example contributing to nutrient and carbon cycling.

Intermittent rivers provide habitats for diverse and unique plant and animal communities. Diversity of intermittent rivers can in fact exceed the richness of perennial ones. This is because different taxa colonize the same locations over a temporal gradient. However, the quantification of biodiversity and ecosystem processes and services that these rivers provide has been restricted to a few studies and a limited number of streams in Serbia and Montenegro.

Climate change is perceived as one of the most serious threats to the aquatic biodiversity, with alterations in drought (and less precipitations) and flooding (and rising precipitations) regime affecting both individual species and the entire aquatic assemblage. Specialist species, such as endemics, are assumed to be more susceptible to disturbance events as their diversity and abundance is often related to the relative habitat quality. On the other hand, generalist species, are relatively more tolerant of a wide range of environmental factors. The occurrence of endemic species in intermittent rivers is in contrast with earlier studies that stressed the absence of endemic taxa in this environment. Recent molecular studies have revealed substantial cryptic diversity within the conventionally described morphospecies that inhabit intermittent streams. A recent example is the discovery of a new species *Mideopsis milankovici* Pešić & Smith, 2020, named after Milutin Milanković, inhabiting intermittent streams in the Mediterranean part of Montenegro.

Part IV: What should we do in the next century?

**NUMERICAL MODELING, FROM WEATHER TO CLIMATE:
PROGRESS ACHIEVED, AND SOME OF THE REASONS
PROMISING FURTHER PROGRESS**

**FEDOR MESINGER¹, KATARINA VELJOVIC²,
SIN CHAN CHOU³, JORGE L. GOMES³, ANDRÉ A. LYRA³,
AND DUSAN JOVIC⁴**

^{1/} Serbian Academy of Sciences and Arts, Belgrade, Serbia
E-mail: fedor.mesinger@gmail.com

^{2/} Faculty of Physics, Univ. of Belgrade, Belgrade, Serbia
E-mail: katarina@ff.bg.ac.rs

*^{3/} Center for Weather Prediction and Climate Studies (CPTEC), INPE,
Cachoeira Paulista, SP, Brazil*
E-mail: chou@cptec.inpe.br

*^{4/} NCEP Environmental Modeling Center (EMC), College Park, MD,
USA*
E-mail: dusan.jovic@gmail.com

Abstract. Milanković’s thinking is summarized, when in 2013 looking for a major “cosmic” problem to embark on using his mathematical talents, Milanković started with weather. But he eventually decided that “at least for the time being”, this was not possible, turning his attention to climate. Indeed, regarding weather, when the time did come, numerous necessary steps had to be taken. Some illustrations of how far this took us are given. Not only regarding the accuracy of the day-to-day forecasts, but eventually also finding “predictability in the midst of chaos”, thus extending lead times of obtainable skill into seasonal, annual, decadal, and even longer climate change time scales. As to the weather, an illustration of progress achieved often the near disappearance of skill difference between the extratropical data rich Northern and data poor Southern hemisphere is taken. If he is looking, we are confident Milanković is pleased to see the skill achieved by a model largely from his part of the world, the Eta model. We show results showing its advantage over the ECMWF model, generally considered as “the benchmark to beat” among multitude of present-day models; and added skill it derives from two of its unique features. One is its “eta” vertical coordinate with coordinate surfaces intersecting topography, and the other its finite-volume vertical advection. The vitality of the extraordinary variety of today’s approaches

to numerical design justifies an optimism expected of further progress. Emergence of skillful seasonal forecasts is yet another reason in that sense. We show an example of again the Eta but now in that role. In climate change area, the need to understand the reason for recent acceleration of global warming is a problem deserving attention. This offers a challenging test for further improvement in what is now referred to as the Earth system modeling.

Key words: Milutin Milanković beginnings, Cut-cell Eta model, Topography in NWP, Eta vs. ECMWF, Finite-volume vertical advection

1. INTRODUCTION

At the centenary of Milanković's seminal book laying the grounds for the analysis of climate changes prompted by astronomical factors, we find it appropriate to recall his thinking that eventually led him to embark on that effort. In 1913, having accepted a professorship in applied mathematics at the University of Belgrade, Milanković was looking for a field in which he could use his mathematical talents. His mathematics professor at high school, Vladimir Varičak, advised him to look "in the kingdom of science" for fields of uninhabited and uncultivated land, because it is in these places where the greatest discoveries might be found. Following his advice, Milanković drew a schematic, with several concentric circles, and mathematics, as a symbol of the Sun, at its center (Milanković 1957). It was shining upon all the "exact" sciences of the next circle, such as physics, celestial mechanics, etc. But it was barely entering the descriptive natural sciences of the circle beyond, meteorology, geophysics, geology, etc. This was where he decided he needed to look and started with meteorology.

Milanković did this by asking a friend and a colleague Pavle Vujević, teaching meteorology and climatology, for main publications summarizing his science. In what he received he found just a little physics, and barely any mathematics. He next asked if there were any works with comprehensive use of mathematics. What he received introduced him to what existed at the time on "solar climate", temperatures that would exist at various latitudes were it not for atmospheric influences—a situation he easily expanded upon by adding the impact of heat conduction to the Earth's interior. But even more stimulating apparently was a paper published by the Vienna Academy of Sciences discussing the distribution

of Solar heating upon the Earth's surface, in which the author started with an equation which was wrong. As a result, all his results were wrong, as well as those of another paper published two years later. Milanković decided this important problem needed to be straightened out, which he did in a comprehensive 80-page paper published the same year. This was the cornerstone of his later work, in which he expanded the effort to analyze the Earth's climate changes that were to have resulted from complex workings of many bodies of the family of our Solar system.

2. WEATHER PREDICTION

But what about Milanković's original idea, meteorology, or weather prediction? Recalling later his thinking of the time (Milanković 1952) he wrote

I was struck looking at the difficulty of the task. The variety of Earth climates bewildered me, clouds of the sky would make me frown, every rain would make me depressed, and when a gust of wind would come by, in particular the Belgrade's koshava, I would ask myself "Who could capture all the whims of Aeolus into mathematical formulas?"

Still later, Milanković (1957) expands on this idea by adding

Irregular distribution of land and sea, relief of continents, oceanic currents and those of the atmosphere, along with its precipitation, changes of the day to night as well as the change of seasons, all of that impacts the thermal and dynamical phenomena of the Earth's atmosphere, and all of that evolves in such a complicated manner that, at least for the time being, it seems impossible to subject these phenomena to a mathematical analysis to a degree which would enable one to foresee their succession" (*Italics by the present authors*).

Consequently, regarding such "intermittent and local" events, Milanković decides "I am not going to deal with those" (1952 p. 57; 1997, p. 466). But the average climate of a place does not change much over centuries, and this was a "great cosmic problem", one that will take years to conquer, but still one he could undertake, being of the best age for such an endeavor. Had he been younger, he would not have had enough knowledge and experience for such an effort, and had he been older, he would not have had the confidence and courage that the youth endows us with, he wrote.

3. “AT LEAST FOR THE TIME BEING”: WEATHER

But what about the Milanković’s prophetic words we emphasized above, “at least for the time being”, regarding weather phenomena, ability to “foresee their succession” via “mathematical analysis”? Indeed, it has taken a good part of the past 100 years to come to the present state when we are able to forecast weather for some days ahead with considerable confidence. This required new knowledge how to use the necessarily incomplete observation of the initial state of the atmosphere and of its lower boundary, how to perform the calculations ahead in time, and the ability to perform the extraordinary volume of calculations required.

And to stay on the right path, also the understanding of the limitations in all of these, including that of the chaotic nature of the atmospheric system. We feel it appropriate to illustrate these achievements by several examples from our own work, given that they to a significant degree originate from the region of the Milanković effort we today celebrate, but even more since they provide some light on prospects of continued progress. Let us start with the initial data problem. Initial data are required for all of the globe, and for all of the atmosphere. Measurements are taken at surface stations, by the release of radiosondes carrying sensors tracked from ground stations; temperature profiles are deduced from satellite radiation measurements, commercial flights take measurements along their flight paths, etc., etc. But except for satellite radiation measurements, most of data coverage comes predominantly from land areas of the globe, and there is considerably more land over Northern Hemisphere than over the Southern one. For that reason, weather prediction skill over the Northern Hemisphere used to be considerably higher than over the Southern.

But by about the beginning of this century skill at the Southern hemisphere has improved compared to that of the Northern so as to become about the same (e.g., Bauer, Thorpe, and Brunet 2015, Fig. 1). As to the prospects for continued increase in numerical weather prediction (NWP) skill—recall the “next hundred years” subject of the conference, what supports our feeling that these prospects are great is the variety of approaches in place today. Note the “Issues and priorities believed in” section of the review article of Mesinger, Rančić and Purser (2018). Of the issues discussed in that review we will emphasize that of the representation of topography in models. Almost all operational models use the terrain-following vertical coordinate, but two other approaches are

pointed out and/or believed to offer prospects for increased skill. These are the “immersed boundary” method, and that of the “cut-cell” schemes. They both use horizontal or quasi-horizontal coordinate surfaces, intersecting topography, and leaving the grid system unchanged. The former designs boundary conditions to treat the topography as is, while the latter cuts the bottoms of lowermost grid cells above ground so as to represent the topography (Mesinger and Veljovic 2020). How does this last option perform?

Deciding with high confidence whether a model difference results in increased skill is not straightforward and is a science discipline in itself. What we chose to do regarding the impact of the choice of the eta coordinate in the Eta model, with its cut-cell discretization, compared to the usual terrain-following choice was a combination of two experiments. First, comparing the performance of the Eta against that of a highly respected model that uses the terrain-following coordinate. Second, comparing the performance of the Eta against itself, when it is changed so as to use the terrain-following coordinate. This changed Eta we refer to as “Eta/sigma”. Our choice of a “highly respected model” was the model of the European Centre for Medium-Range Weather Forecasts (ECMWF, EC later on). The experiments were done by initializing the limited area Eta and Eta/sigma models using initial conditions derived from members of an EC 32-day ensemble and driving those Eta and Eta/sigma members by the lateral boundary conditions derived from their respective EC members. Situation chosen for these experiments was one with a major upper-tropospheric trough crossing the Rocky Mountains during about the first ten days of the experiments. According to several verification scores after the initial about two days of presumably adjustment to interpolation inconsistencies, perhaps surprisingly, during these ten days a convincing advantage of the Eta members was demonstrated. The degree of advantage was such that according to each of the three scores used at some verification times all 21 Eta members scored better than their EC driver members. These verification scores used were the Gilbert or equitable threat score adjusted to unit bias (ETSa, Mesinger 2008), standard root-mean-square difference with respect to EC analysis, and the symmetric extreme dependency score (SEDS, e.g., Wilks 2011), all calculated for 250 hPa wind speeds. The ETSa and SEDS scores were calculated for speeds $> 45 \text{ m s}^{-1}$, with the idea that these speeds at 250 hPa are a good representation of the position of the upper tropospheric jet stream. The advantage of the Eta could be seen also in synoptic features as illustrated

in Fig. 1 by plots of the 250 hPa wind speeds at 4.5-day time of the experiments. The top left plot shows the ensemble average of the EC members over the area of the experiments, the right-hand plot that of the Eta members, and the bottom plot the EC analysis along with 250 hPa height contours.

Our second experiment of rerunning the ensemble using the Eta switched to use sigma, Eta/sigma, perhaps again surprisingly, showed an advantage

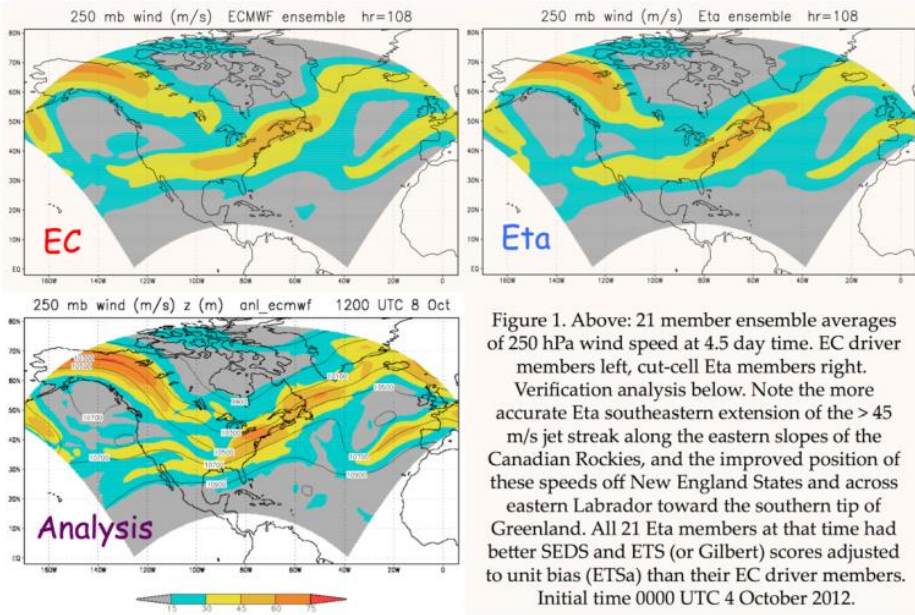


Figure 1. Above: 21 member ensemble averages of 250 hPa wind speed at 4.5 day time. EC driver members left, cut-cell Eta members right. Verification analysis below. Note the more accurate Eta southeastern extension of the > 45 m/s jet streak along the eastern slopes of the Canadian Rockies, and the improved position of these speeds off New England States and across eastern Labrador toward the southern tip of Greenland. All 21 Eta members at that time had better SEDS and ETS (or Gilbert) scores adjusted to unit bias (ETSa) than their EC driver members. Initial time 0000 UTC 4 October 2012.

of the Eta/sigma over the EC as well, although to a smaller degree (Mesinger and Veljovic 2020). Thus, as opposed to four Eta member “wins” of ETSa and one SEDS win with all 21 members over the EC during the 2.25 to 4.5-day time of the experiment, the Eta/sigma recorded a maximum of four ETSa wins of 19 members, and none to that degree according to SEDS scores. But still, a general advantage of the Eta/sigma over the EC following the initial two days and out to about 20 days according to all three scores was quite convincing. So, what could be the main reason for this advantage? In Mesinger and Veljovic (2020) we list several candidate reasons. One of those for which we have some experimental results is the van Leer type finite-volume vertical advection of the Eta (Mesinger and Jovic 2002), compared to the centered “Lorenz-Arakawa” scheme of the earlier Eta codes (Mesinger, Chou, Gomes, et al. 2012, Eq. 2; Metal.2012 further on). The impact of this change was tested on a case of zonda downslope windstorm, this being of interest because of the flow-separation problem of the pre-cut-cell version of the Eta,

discovered by Gallus and Klemp (2000). The zonda situation we chose is illustrated by the sections of surface maps shown in Fig. 2.

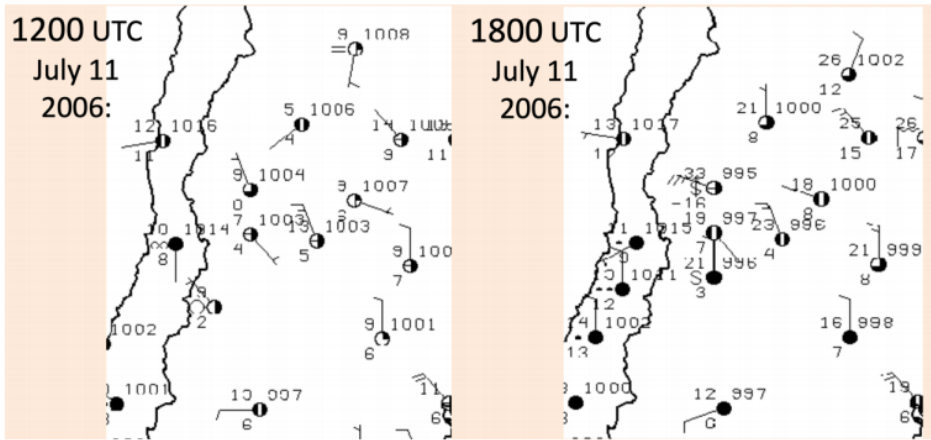


Figure 2: Sections of surface maps over the central region of the Andes, with the station of San Juan (630 m above sea level) about the middle of the plots, showing a temperature increase from 9 to 33° C during the 6 h time difference between the two plots. Valid times of the plots are given in their top left corners.

The case addressed is the same as that discussed in Section 9 of Metal.2012 and in Norte et al. (2008), so that a fair amount of relevant information can be found in these two papers. We shall here expand on results of the forecast illustrated in Fig. 8 of the cited Section. We do this by displaying in Fig. 3 plots of temperatures of the lowermost Eta cells at 33 h, corresponding to the time of the right-hand plot of Fig. 8 of Metal.2012. Note that these plots are generated using the NCAR graphics package so that they show actual temperatures at grid cells as opposed to space interpolated values. While looking at the vertical cross-sections of the referred to Fig. 8 we could only talk about temperatures “in the San Juan area”, but in the plots of the present Fig. 3 we were able to place cross signs at the location of the San Juan station, seen slightly below the centers of the two plots and to the right. The purpose of the two plots of Fig. 3 is to access the impact of the change of the vertical advection scheme of the Eta. To that end, the right-hand plot is the control, corresponding to the forecast result displayed in the right-hand plot of the cited Fig 8, while the present left-hand plot is generated using the same

code except for the finite-volume vertical advection being replaced by the Lorenz-Arakawa scheme, previously used in the Eta.

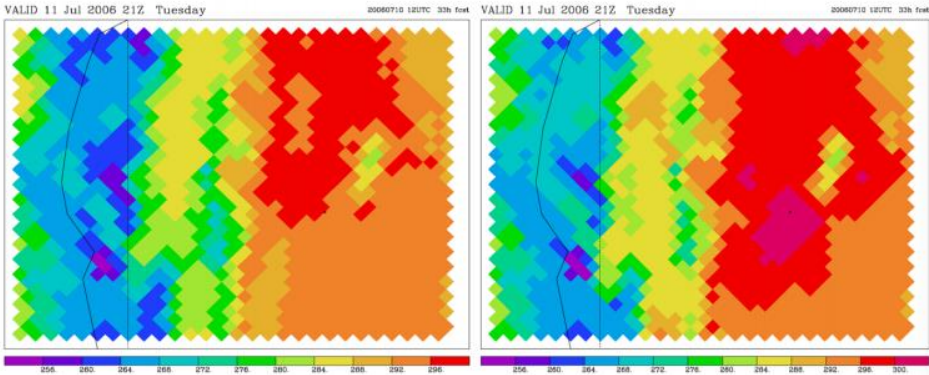


Figure 3: Forecast temperatures at 33 h of the lowest temperature cells of the case discussed in Section 9 of Metal.2012, displayed in the vertical cross section of the right-hand plot of its Fig. 8. The left-hand plot above differs from the right-hand one by having the Eta finite volume vertical advection replaced by the Lorenz-Arakawa finite-difference scheme. The roughly vertical line on the left sides of the plots is the Chile-Argentina border, while the straight line is the 70°W meridian.

The two plots illustrate a considerable impact of the change to the van Leer type vertical advection scheme, and in addition via the display of the actual lowest temperature values within the chosen plot intervals enable an inference of the zonda warming with more confidence than what was possible via the referred to plots of Fig. 8. In looking at the temperature increase in the San Juan region from 24 to 33 h as visible in these Fig. 8 plots, a zonda warming of about 14 K was stated to have been forecast. More precisely, based on temperature intervals of the plots of that figure, the warming was at least 13 K. At 24 h plots corresponding to the 33 h plots of Fig. 3 (not shown), the San Juan cross sign is in both of them inside the interval of 276 to 280 K, thus the temperature at the place is < 280 K. On the right-hand plot above, the cross sign is well within the > 300 K area, showing a zonda warming in the San Juan region of at least 20 K, considerably more than what was visible in cited Fig. 8 of Metal.2012.

As to the impact of the change of the vertical advection scheme, at the left plot above the cross sign is very nearly at the boundary of the temperature cells > and < 296 K. If we take the average of these neighboring cells as much as we can infer it as appropriate, 296 K, and recall the 24-h value of

< 280 K, we deduce the warming of > 16 K, a fair amount more than inferred from plots of Fig. 8 of Metal.2012. Yet, this is still well below the warming of more than 20 K displayed by the right-hand plot of Fig. 3 above, very much in the neighborhood of the observed value shown in our Fig. 2. Thus, we find that Fig. 2 seems to strongly support the possibility of the finite-volume vertical advection being a good candidate for having helped the Eta achieve the advantage over the EC shown in our Fig. 1 and various other Mesinger and Veljovic (2020) results.

One might be puzzled by the generally somewhat colder temperatures over the highest elevations of the Andes with the Lorenz-Arakawa scheme, seen on the left-hand plot of Fig. 3. A possible explanation might be the problem of the scheme in having an unphysical vertical advection from below ground, documented in Metal.2012 to lead to unrealistically cold temperatures in basins subject to persistent upslope winds. Be that as it may, we find that the right-hand panel of Fig. 3 demonstrates a rather realistic forecast of the zonda warming for this quite extraordinary July 2006 case, with maximum warming just in the region of San Juan as recorded on the surface maps of Fig. 2, and of the intensity similar to that observed.

4. “AT LEAST FOR THE TIME BEING”: CLIMATE

But what about the extension of forecasting skill towards the territory Milanković decided for, that of climate?

When it comes to forecasting the specific details of weather, it was Philip Thompson (1957) who first pointed out that there is a limit to how far ahead we can hope to extend the limit of useful weather forecast, because we are able to observe the initial state of the atmosphere at only a limited number of points.

With the then observational network, about a week looked possible, but increasing the observational coverage would help. But in his famous paper Lorenz (1963) demonstrated that no matter how small we were to make our initial error this small error will grow.

This because the atmosphere is a system exhibiting properties of chaos. But the wonderful words of the title of the paper by Shukla (1998) “Predictability in the midst of chaos”, point that even so there are features

we can predict with skill that deserves attention. Changes from El Niño to La Niña, impacting weather phenomena worldwide, are a prominent example.

Time scales closest to those of the traditional NWP, now referred to as subseasonal to seasonal (“S2S”) prediction, are perhaps being in the focus of most major NWP groups (e.g., NASEM 2016). For conclusion of our selection of points of note when looking into the future, we shall include an example of such efforts. It is one employing once again the Eta model, run nested in the CPTEC atmospheric global general circulation model (AGCM).

Five-member Eta Regional Climate Model (RCM) seasonal forecasts were generated in a 10-year reforecasting effort over the South American region, including considerable fractions of the neighboring oceans (Chou et al. 2020). Resulting 12-month sequences, starting with January-February-March (JFM), of the areas of precipitation anomaly correlations > 0.3 of the driver AGCM (red), and of the nested Eta RCM (blue) are shown in Fig. 4, along with a line showing the gain ratio of the regional model over its driver AGCM. Seasonal forecast skill of 0.3 was considered a limit for useful forecast. See Chou et al. (2020) for additional detail.

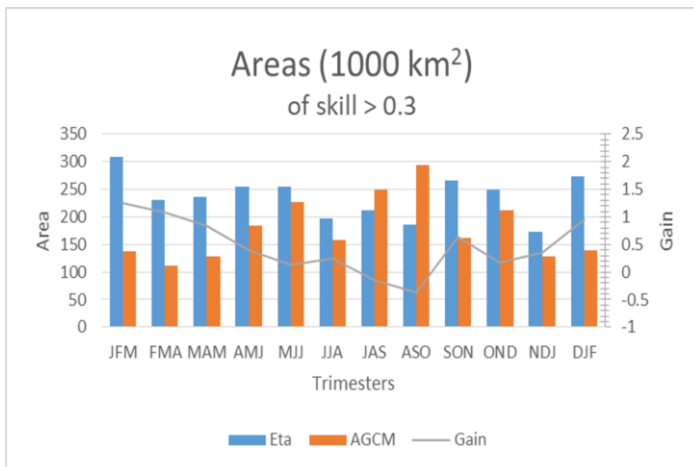


Figure 4: Area of the anomaly correlation > 0.3 of the 3-month five-member ensemble 10- year reforecasts of the Eta RCM (blue), driven by CPTEC AGCM, and those of this driver AGCM (red). Gain ratio of the regional model over its driver AGCM, calculated as the difference of the total area of skill > 0.3 of the Eta over that of the AMCM divided by that of the AGCM, is shown by the gray line. From Chou et al. (2020).

We see in the figure that in 10 out of the 12 trimesters the Eta RCM gains over its driver AGCM in the area with useful precipitation skill, its advantage being particularly prominent during the rainy season. Needless to say, a global Eta-based model would be expected to result in at least about the same degree of improvement, given manpower and computer resources for that development. For an effort in that direction, note (Latinović et al. 2018). As pointed out (NASEM 2016) numerous other activities in this area are taking place, our Fig. 4 being just a glimpse at one of the many promising results accomplished. What about still longer time scales, those of the referred to changes from El Niño to La Niña, and related, e.g., the so called El Niño Southern Oscillation (“ENSO”) and more, and then still longer, covering those of the important and even critical climate change issues?

In all of those extensive activities are taking place, but understandably, those of the climate change taking place receive interest well beyond just science. As to the science, numerical models are used to project what we should expect to happen to our planet’s climate as a result of various possible inputs of greenhouse gasses (GHGs) to the atmosphere, but at the same time need to be verified as able to emulate the changes that are happening today. Regarding the former, note calculations of Hansen et al. (2013) of the equilibrium temperature changes following successive doublings of the atmospheric CO₂; a future humanity obviously must not permit to occur. As to the latter, challenges are summarized perhaps best in a recent communication by Hansen and Sato (2020).

Major numerical modeling groups participate in regular Intergovernmental Panel’s on Climate Change (IPCC) Assessment Reports (AR), and at the time of this writing preparation of the IPCC Sixth Assessment Report (AR6) is in progress. People working on the Earth system models used for various tasks of the AR6 of course do their best to have their models agree with the change of the Earth climate as it is observed. Problem are that observations are not perfect and not complete, and that the agreement with the climate as observed can be improved by implementing model changes that are not those which would be correct from the physical point of view. Wrong steps of course tend eventually to be identified, but this is a process that takes time. The cited recent communication of Hansen and Sato (2020) points out, Fig. 5, that the global warming has accelerated in the past 6-7 years, and that this has happened in spite of the two well-known forcings, those of GHGs and

solar, taken together having diminished in that time. The only explanation Hansen and Sato see is that the negative aerosol forcing must have diminished during that time. Aerosol forcing is unfortunately not measured, even though this would be possible to do, this therefore being an urgent implementation task.

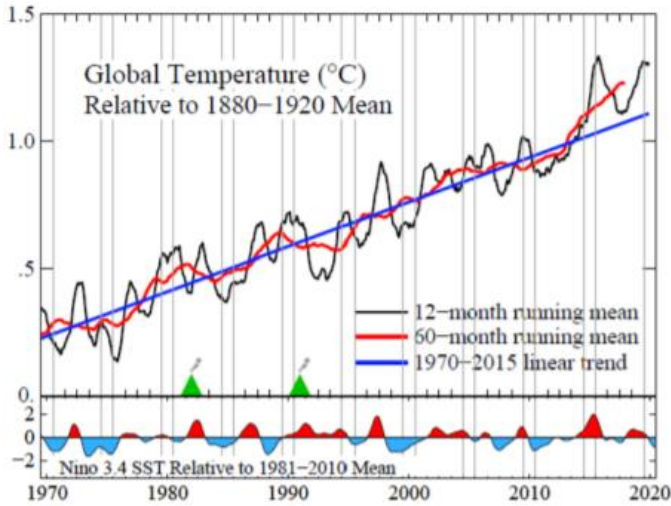


Figure 5: Global near-surface temperatures (°C) relative to 1880-1920 mean according to NASA Goddard Institute for Space Studies (GISS), GISTEMP analysis, along with information on major volcanic eruptions and the intensity of El Niño. From (Hansen and Sato 2020).

5. “TAKE HOME” POINTS

In the spirit of one motivation idea of this anniversary conference, a look ahead, we have pointed out to some evidence that at “weather” time scales, up to about ten days, in spite of considerable improvement of the skill of numerical models there is obvious room for further progress. In particular,

- Terrain representation in just about all “production” models can be considerably better than it is,
- Finite-volume numerical cores deserve attention,
- Diversity of dynamical core approaches is crucial in enabling further progress.

As to the subseasonal to seasonal, (S2S), and climate change time scales,

- Useful skill at S2S efforts exists already, and can only improve,
- Realism of “Earth system models” will certainly increase, and availability of missing information on aerosols (Hansen and Sato 2020) is one necessary step of that road.

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UNDERSTANDING CLIMATE HISTORY TO PROJECT FUTURE CLIMATE CHANGE

GORDON MCBEAN

*CM, FRSC, FAMS, FAGU, FIUGG Western University and Institute for
Catastrophic Loss Reduction, London, Ontario, Canada*

E-mail: gmcbear@uwo.ca

Abstract. Planet Earth is now facing the growing challenge of climate change. The active responses of governments and people have been motivated by the science and its assessments that demonstrate the causes of climate change and projections of future climate change and its impacts. Understanding the climates of the past have been a strong factor in confirming our scientific understanding and in terms of verifying global climate models that can then used to project the possible futures. The Milankovic theory of climate change has provided a basis for understanding and testing. This article provides a historic perspective of the how understanding climate history and science has enabled projections of future climate change and its role in motivating global action. The climate science assessments of the Intergovernmental Panel on Climate Change are used to highlight the important scientific advances and their interrelationships influences on policy.

Key words: Milutin Milanković, Climate history, Projecting climate futures, International climate change actions

1. INTRODUCTION

Over the past two centuries, the very large growth of the human population and the industrial revolution on Planet Earth have led to massive increases in emissions of chemical substances and gases into the atmosphere, terrestrial ecosystems and the oceans. The scientific consensus is that our planet has entered the Anthropocene, the age of dominant humans, a new geologic epoch defined by our own massive impact on the planet [51]. The UN Secretary-General António Guterres at the 2019 Climate Action Summit stated [58]: “*Climate change is the defining challenge of our time.*” There is the need to address climate change within the Global Agenda 2030, which also includes the

Sustainable Development Goals and the Sendai Framework for Disaster Risk Reduction [33]. The World Economic Forum [56] 2020 Global Risk Report [57] (published in January 2020) ranked by impact and likelihood, the global risks (*an uncertain event or condition that, if it occurs, can cause significant negative impacts for several countries or industries within the next 10 years*). Environmental risks were ranked very high with Climate Action Failure (both mitigation and adaptation) as the number one risk by impact and the number two by likelihood. Extreme weather events (storms, floods, ...) causing major property, infrastructure, and/or environmental damage as well as loss of human life, were ranked as the highest in likelihood and 4th highest in terms in impacts. These two risks are highly linked. Biodiversity, ranked as the 3rd highest risk in terms of impact and 4th highest in terms of likelihood, and Water Crises, ranked as the 5th highest in impact and 8th highest in likelihood, and are both also linked, at least in part, to climate change.

2. FOUNDATIONS OF CLIMATE SCIENCE

The scientific basis [53] for understanding the climate system and its variability goes back over millennia, building on fundamental understanding of the physics and chemistry of the climate system. In 1824, almost 200 years ago, Fourier [8] developed the understanding of the greenhouse effect through the roles of the visible light from the Sun heating up the Earth and the greenhouse gases (water vapour, carbon dioxide, methane and others) absorbing some of the Earth's outgoing radiation and sending it back down to the surface, further warming the Earth. Arrhenius (1896) [1] concluded that doubling the CO₂ in the atmosphere would raise the Earth's global temperature about 5-6°C. The role of solar radiation and the Earth's orbit around the Sun was enunciated in 1920 in the mathematical theories of thermal phenomenon by Milankovitch in 1920 [35]. He followed this up with climate theories in 1930 [36] and their role in glaciers in 1941[37]. This fundamental science, addressing the greenhouse gas effects and the solar radiation and planetary orbits – linked together - has been the basis for what we are now or should be doing in responding to the climate crisis.

Milankovitch's astronomical theory [43] of the ice ages was fully verified in the seminal paper by Hays et al. (1976) [12] who called it the "*pacemaker of the ice-ages*". The analysis was based upon the analysis of oxygen isotopic data from deep-sea sedimentary cores which have been

further analyzed in detail by Shackleton et al. (1990) [49] who provided an alternative astronomical calibration of the lower Pleistocene timescale. Ocean cores provided excellent material for high resolution stable oxygen isotope analysis through the past few million years which matched well with orbital models and were in accord with expectations based upon the Milankovitch hypothesis.

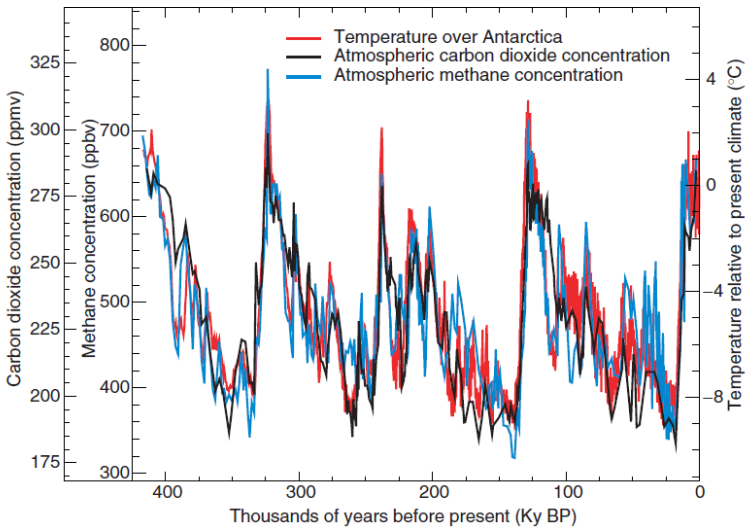


Figure 1: Variations of temperature, methane and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctica [24][4][7][44]50]

Figure 1 shows the variations of temperature and the greenhouse gases, carbon dioxide and methane, over the past 400,000 years, a period of about 4 ice-age domains and demonstrates interactions within the climate system. As the Earth’s orbit around the Sun varies in shape and tilt, the incoming solar radiative energy varies, following the Milankovitch cycles. The reduction in incoming energy results in a cooler climate – the red line. The cooling oceans absorb carbon dioxide from the atmosphere reducing the greenhouse effect, which amplifies the cooling, bringing the red line down further. As the climate cools further, sea ice and glaciers grow leading to the reflection of more solar energy, enhancing the cooling further – so that, as in Figure 1, there is a reduction in global mean temperature of 7-8°C with large glaciation in the north, the ice age about 350,000 years ago. As the Milankovitch components of orbit and earth tilt evolve, the solar radiation increases, resulting in a rapid warming, more rapid than the cooling, as the oceans release the greenhouse gases and the

melting ice reduces the reflection of solar energy. This cycle continues with ice ages about 100,000 years. The Milankovitch cycle interacts with the atmospheric, ocean, terrestrial and cryosphere components in the time changing climate. This provides an explanation of planetary history and a test bed for development and testing integrated climate models, providing, through understanding climate history, enabled projections of future climate.

3. ENHANCING CLIMATE SCIENCE FOR ACTION

Climate change became a political issue, initially in the late 1970's and more so in the mid-late 1980's, leading to enhanced scientific studies of the global climate system and greatly strengthened the knowledge base, building on the fundamental science of Newton, Fourier, Milankovitch and others. In 1979, the First World Climate Conference received the scientific evidence confirming the long-term concerns about a changing climate.

The International Council of Scientific Unions (ICSU) (now the International Science Council) [17] and World Meteorological Organization (WMO) [59] created, in 1980, the World Climate Research Programme (WCRP) [55], with the scientific objectives: to determine: *the predictability of climate; and the effect of human activities on climate.* The Intergovernmental Oceanographic Commission (IOC) [15] became a co-sponsor in 1992. With the rising international concerns about climate change and related issues of global environmental change, plus emerging discussions on sustainable development, ICSU founded the International Geosphere-Biosphere Programme (IGBP) [16] to: *study earth system science and to help guide society onto a sustainable pathway during rapid global change.* In 1991, the IGBP created the Past Global Changes (PAGES) project to improve our understanding of past changes in the Earth system in order to improve projections of the future. Their website provides links, for example, to information on “*How the Sun Affects Climate: Solar and Milankovitch Cycles*” [54].

4. ASSESSMENTS OF CLIMATE SCIENCE FOR POLICY

With the increasing global concern about the climate and possible human-caused climate change, the Intergovernmental Panel on Climate Change (IPCC) [18] was created in 1988 to: *(i) assess available scientific*

information on climate change, (ii) assess the environmental and socio-economic impacts of climate change, and (iii) formulate response strategies. Over the years, the scientific programs planned and coordinated by the WCRP and the IGBP (now part of Future Earth [10], created by merging IGBP with other international projects) have been the major source of scientific results for the IPCC assessments.

The IPCC is structured with three Working Groups: Working Group I assesses the physical science underpinning past, present, and future climate change and how it is changing in response to human activity – and is the focus of this article. Working Group II assesses the impacts, adaptation and vulnerabilities related to climate change and Working Group III focuses on climate change mitigation, reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere. The advancements in science and the increased warming of the climate system and concentrations of greenhouses have been reflected in the IPCC’s assessments.

The IPCC First Assessment Report (FAR) [20], completed in 1990, includes Chapter 2 on Radiative Forcing of Climate, addressing the issue of climate variability due to orbital changes. As they said: *“Variations in climate on time-scales ranging from 10,000 to 100,000 years, including the major glacial/interglacial cycles during the Quaternary period, are believed to be initiated by variations in the Earth’s orbital parameters which in turn influence the latitudinal and seasonal variation of solar energy received by the Earth (the Milankovitch Effect).”* They went on to comment on the factors seen in Figure 1. The orbital parameters and the Earth’s climate provide a *“compelling argument in favour of the Milankovitch theory”*, while the internal feedback processes, as discussed above, are very important.

Chapter 7, on Observed Climate Variations and Change [21], concluded that the Milankovitch orbital effects (Berger, 1980) [2] *“appear to be correlated with the glacial-interglacial cycle since glacials arise when solar radiation is least in the extra-tropical Northern Hemisphere summer”*. Regarding the important question - has the climate changed and is the change due to human activities - the FAR states: *“The observed increase (in temperatures) could be largely due to natural variability; alternatively this variability and other man-made factors could have offset a still larger man-made greenhouse warming.”*

The Report also laid out a scientific action plan [30] for improved prediction of global climate change to narrowing the uncertainties This IPCC First Assessment Report (FAR) was presented to the Second World Climate Conference [48] in 1990 and the Conference, including many heads of state, made a recommendation to the 1992 United Nations Conference on Environment and Development (UNCED) [52], also called the Earth Summit, held in Rio de Janeiro, which created the Framework Convention on Climate Change (UNFCCC) [9].

The IPCC Second Assessment Report (1995) (SAR) [22] examined the many issues of climate change including analyses of changes in sea examining the geological and geophysical effects (Chapter 7) with a focus on long-term sea-level changes and issues of post-glacial rebound [6][39][40]. Among their conclusions were that adjustments to the effects of deglaciation throughout the Holocene period (last 10,000 years) are important [42] and the use of paleo-data and the Milankovitch connections were important in evaluation of internal variability and feedbacks in climate system [41]. Adjustments of the post-glacial rebound-related land movements as estimated from tide gauge records and use of Peltier's model [42] were cited.

The Assessment [31] included the recommendations: *“to build confidence in the decade-to-century time-scale natural variability simulated by models, there is a need to compare model attempts to mimic the climate of the last 1000 years with variability estimates from paleo-climate data with comparable time resolution. the need to identify the forcings, for example solar, volcanoes, deforestation, ... phase lags and leads at very large spatial scales which are potentially testable given appropriate paleo-data.”* Following the FAR statement, the SAR examined the whether the climate was changing and its cause and noted that: *“Changes in climate have occurred in the distant past as the distribution of continents and their landscapes have changed, as the so-called Milankovitch changes in the orbit of the Earth and the Earth's tilt relative to the ecliptic plane have varied the insolation received on Earth, and as the composition of the atmosphere has changed, all through natural processes.”* *“More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies”* and that *“The vertical patterns of change are also inconsistent with those expected for solar and volcanic forcing”* were conclusions.

Building on this information and atmospheric temperature analyses and model studies of Santer [47] and Mann [29], the conclusion was that: *“the balance of evidence suggests a discernible human influence on climate”*.

The IPCC Second Assessment Report was presented to the 1996 Climate Convention Conference of Parties (CoP2), in Geneva. The delegates agreed to the Geneva Ministerial Declaration [11], which stated: *“2. Recognize and endorse the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as currently the most comprehensive and authoritative assessment of the science of climate change, its impacts and response options now available. ... a scientific basis for urgently strengthening action at the global, regional and national levels, particularly action by Parties ... 3. Believe that the findings of the Second Assessment Report indicate that the continued rise of greenhouse gas concentrations in the atmosphere will lead to dangerous interference with the climate system, given the serious risk of an increase in temperature and particularly the very high rate of temperature change.”* The Geneva Declaration was presented at the opening of the 1997 CoP3 in Kyoto and contributed to the agreement of the Kyoto Protocol [27].

The Third Assessment Report (TAR) [24] concluded that: *“There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.”* Chapter 2 on Observed Climate Variability and Change was especially important as it examined the temperature of the past 1000 years and addressed the questions of the “little ice age”, the “Medieval warm period” and the volcanic and solar effects in the recent record. The conclusion is that the *“rate and magnitude of global surface 20th century warming is likely to have been the largest of the millennium, with the 1990s and 1998 likely to have been the warmest decade and year, respectively in the Northern Hemisphere”*. The Assessment examined the Holocene, which began about 11,000 to 10,000 before the present.

The early Holocene was generally warmer than the 20th century with variations between regions. Ice cores from northwest Canada (Ritchie) [46] documented an *“early Holocene Milankovitch thermal maximum”*. Chapter 6 of the Assessment, on the Radiative Forcing of Climate Change, examined atmosphere-ocean general circulation models (AOGCM) and

compared present-day versus paleoclimate (e.g., last glacial maximum) simulations, including those of Rind et al. (1989) [45] and Berger et al. (1993) [3].

The 2013 IPCC Fifth Assessment Report’s Chapter 5 [28] on Information from Paleoclimate Archives included that: *“Recent modelling work provides strong support for the important role of variations in the Earth’s orbital parameters in generating long-term climate variability. In particular, new simulations with GCMs (Carlson et al., 2012) [5]; Herrington and Poulsen, 2012 [14]) support the fundamental premise of the Milankovitch theory that a reduction in NH summer insolation generates sufficient cooling to initiate ice sheet growth”*. Helama et al. (2010) [13] examined Milankovitch solar forcing of past Holocene climates. The Fifth Assessment Reports were provided to the UN Climate Convention Conference of Parties in 2015, in Paris, leading The Paris Agreement [38]. The next full IPCC Assessments will be published in 2021.

Throughout the now almost 30 years of IPCC scientific assessments, there has been examination and support of the Milankovitch theory and its utilization in understanding the climate system and assisting in the development and verification of projection models, and its importance in terms of providing international climate science assessments addressing the IPCC objectives and the international policy dimensions.

5. SEEING THE FUTURE – PREDICTION

To address the issues for sustainable development, there is an essential need for science-informed decision making [33]. There are significant issues of sciences and policy on how to “see the future”. To look ahead to the future, we need to have evidence-based predictions of our global system, including environmental, societal and technological changes (Figure 2, left).

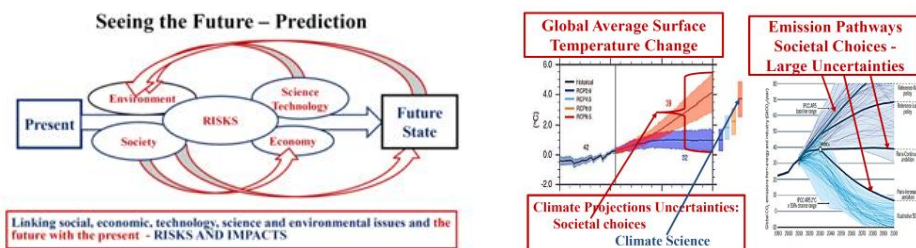


Figure 2: *Seeing the Future – Prediction. The interactions between social, economic, science and technology and environmental issues with feedbacks (left)[32]. Choices in responding to climate change – and their uncertainties – climate science and societal choices (right). (Based on IPCC, 2014 Assessment [26].)*

Predictions [32] of future states require understanding and incorporating the implications of science and technology and society in iterative ways, recognizing that changes in technology result in changes in society and vice versa. Further, as the future state becomes clearer for a specific projection based on the “best” estimates of technological and societal changes, these may “feedback” into the societal response, resulting in the modifications to the prediction of the future state. A fundamental role of the science and technology community is to work closely with the social science community to enable the prediction of future states through an integrated, continuously iterative process of refinement to reduce uncertainty and provide the “best” estimates of futures states as well as clarification of the assumptions inherent in the prediction such that the societal processes can, when possible and appropriate, modify societal changes.

For some natural science issues, such as the tides and related lunar orbits, there are laws of physics that relate the present state to the future state. Milankovitch theory and cycles built on laws of physics to provide the driving forces for variations in solar radiation energy. Projecting climate over the next century not only includes the uncertainties in the present state and the natural scientific relationships, but, equally importantly, the actions that societies will or will not take to reduce their interference with the climate system through emissions of greenhouse gases and the changes in the conditions of the planetary surface. Seeing the future climate (Figure 2, right) means understanding the climate as a natural system and how it changes with increasing greenhouse gas concentrations

and, also understanding human societies and their choices on greenhouse gas emissions resulting in changing the concentrations. There is uncertainty in the natural science models for projecting the temperature change, depending on which emissions scenario will happen in the decades to come.

There is even larger uncertainty on which emission scenario global society will effectively follow. It is very important to understand the interconnectivity between actions and responses across and around the planet with its major societal, logical and philosophical issues. Understanding science, all sciences, is a fundamental way to look ahead – see how things are now and use relationships to see the future. Uncertainty in the natural science models’ projections of temperature change for different emission scenarios are smaller than the larger uncertainty on which emission scenario global society will effectively enact.

As shown schematically, projections or predictions of future states require understanding and incorporating the implications of science and technology and society in iterative ways, recognizing that changes in technology result in changes in society and vice versa. Further, as the future state becomes clearer for a specific projection based on the “*best*” estimates of technological and societal changes, these may “*feedback*” into the societal response, resulting in the modifications to the prediction of the future state.

There is need for the natural (physical-chemical-biological-geophysical-mathematical...) sciences and technology communities is to work closely with the social science communities to enable the prediction of future states through an integrated, continuously iterative process of refinement to reduce uncertainty and help to provide the “*best*” estimates of futures states.

6. CONCLUDING COMMENTS

Over the past decades, Planet Earth has seen a changing climate and the scientific understanding of the complex climate system has been greatly enhanced, through leading scientists who applied fundamental scientific thinking to develop and test hypotheses and theories, leading to understanding and predictions of the future. Professor M. Milankovitch

was one of those scientists. His development of the Milankovitch theory and the explanations of the driving forces for the last million plus years of climate and the ice ages provided a basis for climate system scientific understanding. He continued his contributions over decades and his science has provided a basis for many scientists to further develop and extend our global understanding of the complex climate system enabling predictions.

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ROLE OF CLIMATE IN GLOBAL CHANGE – FROM MILANKOVITCH’S TIME UNTIL END OF THE 21ST CENTURY

SLOBODAN P. SIMONOVIĆ

The University of Western Ontario, Department of Civil and Environmental Engineering, London, Ontario, Canada
E-mail: simonovic@uwo.ca

Abstract. The focus of this paper is on the role climate change is playing in global change. Feedbacks play key roles in Earth’s short-term weather and long-term climate. Milutin Milankovitch developed a theory that the long-term, collective effects of changes in Earth’s position relative to the Sun are a strong driver of Earth’s long-term climate. Milankovitch cycles provide a strong framework for understanding long-term changes in Earth’s climate. They cannot account for the current period of rapid warming. Presented work is based on the global assessment model ANEMI which is using as the main driver of climate change the greenhouse gas emissions, which are in turn driven by energy consumption from a growing population. Set of simulation experiments with the model confirms that climate plays an important role in the performance of Earth system. The future integration of long term climate change impacts (Milankovitch cycles) and short term drivers (greenhouse gasses emissions) will provide deeper understanding of the climate impacts on global change and guide future mitigation and adaptation actions.

Key words: Milutin Milanković, Global change, Climate change, System dynamics, Modelling

1. INTRODUCTION

Global change is being realized as a close consequence of changing climate, creating the need to consider environmental problems and their interactions with the Earth as a system. The Earth system is composed of biological, physical, chemical, and human elements that form a network of feedbacks through their interconnections. The concept of global change

becomes increasingly important as the components of the Earth system such as population, economic productivity, climate, food production, and hydrology are interlinked through dynamic non-linear feedback processes. Within this system, changes in one component inevitably lead to changes in another. The society-biosphere-climate model presented here takes an integrated assessment approach to simulating global change. It consists of eleven individual sectors that reproduce the main characteristics of the climate, carbon cycle, energy - economy, land use, food production, persistent pollution, population, hydrologic cycle, water demand, water supply and water quality sectors at a global scale [1, 2, 3].

The focus of this presentation is on the role climate change is playing in global change. Feedbacks play key roles in Earth's short-term weather and long-term climate. A century ago, Serbian scientist Milutin Milankovitch [4] developed a theory that the long-term, collective effects of changes in Earth's position relative to the Sun are a strong driver of Earth's long-term climate, and are responsible for triggering the beginning and end of glaciation periods (Ice Ages). Specifically, he examined how variations in three types of Earth orbital movements affect how much solar radiation (known as insolation) reaches the top of Earth's atmosphere as well as where the insolation reaches. These cyclical orbital movements, which became known as the „Milankovitch cycles“, cause variations of up to 25 percent in the amount of incoming insolation at Earth's mid-latitudes (the areas of our planet located between about 30 and 60 degrees north and south of the equator). Milankovitch cycles provide a strong framework for understanding long-term changes in Earth's climate. They cannot account for the current period of rapid warming Earth has experienced since the pre-Industrial period (the period between 1850 and 1900), and particularly since the mid-20th Century. Milankovitch cycles operate on long time scales, ranging from tens of thousands to hundreds of thousands of years. In contrast, Earth's current warming has taken place over time scales of decades to centuries. However, Milankovitch cycles are one important factor that contributes to climate change, both past and present.

Presented work is based on the global assessment model ANEMI [1, 2, 3] which is implemented in a system dynamics modelling interface called Vensim DSS [5], which emphasizes the roles of nonlinearity and feedback in determining system behaviour. ANEMI model climate sector is discussed in details after introduction of the model (Section 2) and use of

the model to investigate the role of climate change in global change (Section 3). The paper ends with concluding comments in Section 4.

2. ANEMI GLOBAL ASSESSMENT MODEL

This chapter presents the ANEMI model, which is currently in version 3 [3], built upon the first two iterations of ANEMI [1, 2]. The model shares the same system dynamics simulation paradigm that was used in the previous iterations of ANEMI, in that feedbacks and delays are used to drive system behaviour. ANEMI3 is a type of integrated assessment model that describes the state of and interactions between model sub-systems that compose the Earth system. The main sub-systems or ‘sectors’ used are that of the climate system, carbon, nutrient, and hydrologic cycles, population dynamics, land use, food production, sea level rise, energy production, global economy, persistent pollution, water demand, and water supply development.

2.1 ANEMI model structure

Each individual sector in the model describes the relevant feedbacks that drive the state variables in the sector. Connections between sectors form intersectoral feedbacks responsible for the functioning of the Earth system. It is the intersectoral feedbacks that allow us to represent feedbacks that drive global changes in the Earth system. Feedbacks driving global change are now evident, while it is expected that negative feedbacks acting on population and economic growth may be more evident in the future. From a system dynamics perspective, effective policymaking should be based on addressing the feedback structure of a system, not only on modifying the system parameters. This viewpoint is what makes the ANEMI3 model unique and useful in a time when global modelling is becoming progressively more complex.

The boundary of the model is defined by the problem that is being explored. In this paper, we are modelling the role of climate in various aspects of global change. Therefore, the spatial scale of the model is

mainly one that is global. In some sectors, the stocks are disaggregated to capture material flows on a sub-global scale, but not at a level that is location specific. This spatial scale limits the level of detail that can be used to describe the flows that act to change the model stocks, however it

allows us to effectively analyze feedbacks between water resources and other model sectors on a global scale.

The highly endogenous structure and coupling of sub-systems in the ANEMI3 model are part of its novelty in the realm of integrated assessment modelling. Because of this, feedback processes are responsible for the behaviour that is exhibited in model runs. The model sectors that comprise the ANEMI3 model are that of the climate system, carbon, nutrient, and hydrologic cycles, population dynamics, land use, food production, sea level rise, energy production, global economy, persistent pollution, water demand, and water supply development as shown in Figure 1. Feedback loops between sectors, or intersectoral feedback loops are responsible for global change in this Earth system. Intersectoral feedbacks in the ANEMI3 model allow for the representation of various aspects of global change. In the Figure 1 diagram alone there is a total of 89 possible intersectoral feedback loops. The size of the feedback loops range from 2 to 9 sectors included out of the 10 that are shown. Creating a causal loop diagram from these connections between model sectors allows us to view the feedbacks that are created by combining model sectors in this way.

2.2 ANEMI model climate sector

The climate sector of ANEMI3, as in previous versions, is based on the DICE model of Nordhaus [6]. In this sector, the dynamics of heat exchange between the deep ocean and the combined upper ocean and atmospheric layers are modelled, along with a cooling effect that acts to limit the rate of temperature increase. Identifying the feedbacks that drive this simple climate system allow us to speculate on how the system will function over time. The climate sub-system is driven by two feedback loops. The first being a feedback cooling effect, while the second represents the diffusion of heat in the atmospheric stock to the ocean stock. Both of these negative feedbacks act to dampen the systems response to radiative forcing which comes from increased greenhouse gas concentrations in the carbon cycle and greenhouse gas sub-systems.

Based on the structure of this simplified climate system, one might expect it to predict global temperature values on the lower end of the spectrum. This is because positive feedbacks related to climate change such as methane release from tundra regions and change in albedo as global ice

cover melts are not included, which have the potential to accelerate increases in global temperatures.



Figure 1: High-level feedback structure of the ANEMIS model illustrated as a causal loop diagram

The stock and flow diagram of this model is given in Fig. 3. Two stocks are used to quantify the current global temperature of the atmosphere and oceans in response to external radiative forcing caused by greenhouse gases that are divided into CO₂, methane, nitrogen dioxide, chlorofluorocarbons, and others. Diffusion of heat between these two stocks results in heat being transferred from the atmosphere stock to the ocean stock which acts as a heat sink.

Radiative forcing acts to increase the flow that changes the temperature of the atmosphere stock and is based on the relative change of the greenhouse gases considered from their preindustrial levels. The mathematical description of the atmospheric and upper ocean temperature stock is given by,

$$T_{Auo} = \int CT_{Auo} \cdot dt \quad [^{\circ}\text{C}] \tag{1}$$

where T_{AUO} represents the temperature of the atmosphere and upper ocean and CT_{AUO} is the rate at which T_{AUO} is changing ($^{\circ}\text{C}/\text{year}$).

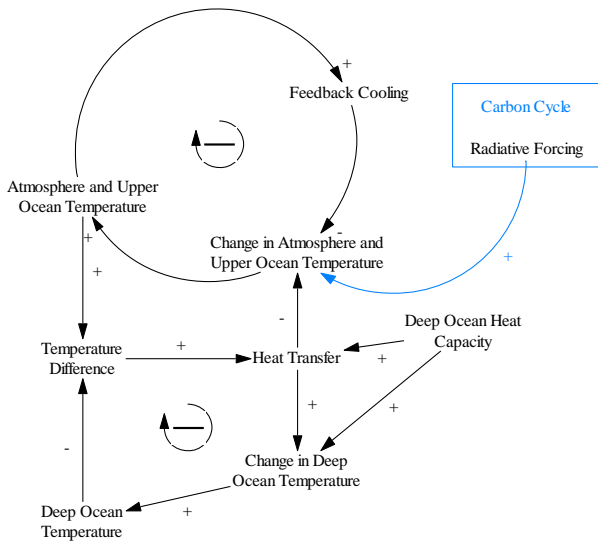


Figure 2: Causal loop diagram of the ANEMI3 climate sector.

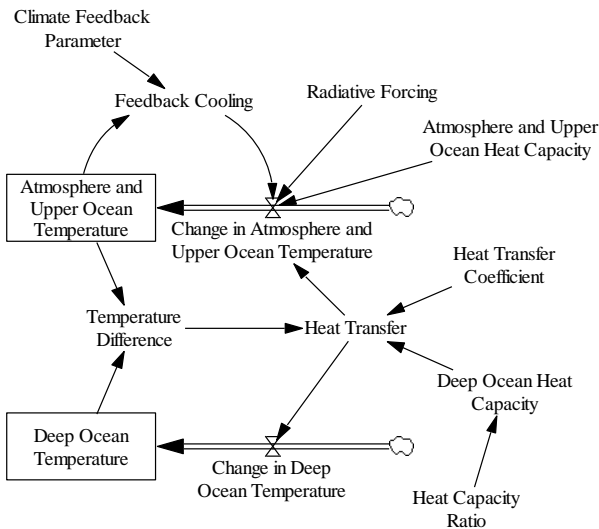


Figure 3: Stock and flow diagram of the ANEMI3 climate sector.

The deep ocean temperature, T_{DO} is defined as,

$$T_{DO} = \int CT_{DO} \cdot dt \quad [^{\circ}\text{C}] \quad (2)$$

where CT_{DO} is the change in temperature of the deep ocean stock ($^{\circ}\text{C}/\text{year}$). The change in temperature of the atmospheric and upper ocean stock is calculated based on the difference between radiative forcing, heat transfer from the deep ocean stock and the heat capacity of the atmospheric and upper ocean stock,

$$CT_{AUO} = \frac{F - f_H - HT}{HC_{AUO}} \quad [^{\circ}\text{C}/\text{year}] \quad (3)$$

where:

$F = \text{Radiative forcing } [W/m^2]$

$f_H = \text{Feedback cooling effect } [W/m^2]$

$HT = \text{Heat transfer between atmosphere and upper ocean to deep ocean } [W/m^2]$

$HC_{AUO} = \text{Heat capacity of atmosphere and upper ocean } [W \cdot (\text{year} / ^{\circ}\text{C} \text{ m}^2)]$

The change in temperature of the deep ocean stock, CT_{DO} depends on the heat transfer from the atmosphere and upper ocean layer above, and the heat capacity of the deep ocean stock,

$$CT_{DO} = \frac{HT}{HC_{DO}} \quad [^{\circ}\text{C}/\text{year}] \quad (4)$$

where:

$HC_{DO} = \text{Heat capacity of deep ocean layer } [W \cdot (\text{year} / ^{\circ}\text{C} \text{ m}^2)]$

Heat capacity of the deep ocean layer is calculated by,

$$HC_{DO} = R_{HC} \cdot C_{HT} \quad [W \cdot (\text{year} / ^{\circ}\text{C} \text{ m}^2)] \quad (5)$$

where:

R_{HC} = Heat capacity ratio [$W / m^2 \cdot ^\circ C$]

C_{HT} = Heat transfer coefficient [year]

The transfer of heat between the atmosphere and upper ocean and deep ocean layers is dependent upon the difference in temperature between them, the heat capacity of the deep ocean layer and heat transfer coefficient.

$$HT = (T_{AUO} - T_{DO}) \frac{HC_{DO}}{C_{HT}} \quad [W/m^2] \quad (6)$$

3. ROLE OF CLIMATE IN GLOBAL CHANGE

Climate change is likely to raise the global average temperature by over 2 degrees C by the year 2100 relative to the 1850-1900 period [7]. As a result, water in the hydrologic cycle is expected to move faster resulting in more extreme and frequent rainfall and streamflow. As ocean temperature rises more moisture will enter the atmosphere resulting in greater amounts of rainfall on land on average. Therefore, there will be more available surface water in total, but potentially less available water in time and space for human use due to the expected shifts in global rainfall patterns. Increased surface temperatures are also expected to be linked to more frequent and severe heat waves that have the potential to increase mortality rates in young and elderly demographics in certain areas of the World.

In addition, more areas will become feasible for new agriculture [8], potentially allowing for greater food production.

3.1 ANEMI model performance

Many of the variables in ANEMI3 do not have historically observed counter parts on a global scale, but there are key variables in each sector that can be compared to historical data. One thing to note in this comparison is that on a global scale, there are many datasets that are incomplete (data is only recorded for certain regions), inconsistent

(different recording methodologies used across regions, recording is done at irregular intervals), and at times, unreliable. However, there is still value in comparing the model to the real world in any way possible to see that it reproduces the behaviour of the sub-systems that are being represented. Note that the goal is not to reproduce the numbers from the data, but build confidence in the model's ability to generate realistic system behaviours in order to build confidence in future behaviours that arise, as well as policies that are implemented to alter them.

For baseline model comparison and climate sector performance assessment the NASA [9] global atmospheric temperature data are used. The variation in global temperatures due to climate change from the year 1980 are shown in Figure 4. From 1980 to 2018 the ANEMI3 model predicts a global temperature change of 0.87 degrees, while the observed NASA data reports a value of 0.6 degrees. The simplified climate system in ANEMI3 is not able or designed to capture the annual variation in global temperatures that are present in the observed NASA data. The behavioural mode is similar, with a slightly higher slope obtained by the ANEMI3. More comparisons are made in Section 4.1.1 with regards to projected change in global temperature change.

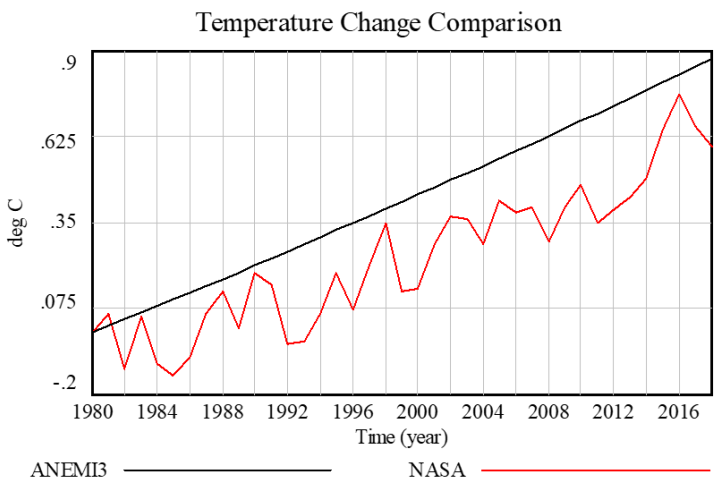


Figure 4: Global temperature change from 1980-2018 comparison between ANEMI3 climate sector and NASA observed data.

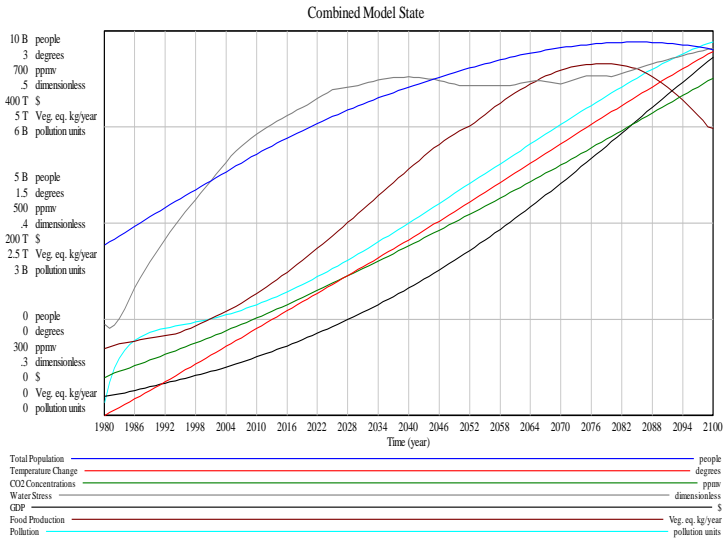


Figure 5: ANEMI3 model performance for the period 1980 - 2100

3.2 Impacts of climate change on the Earth system

In this section the impacts of climate change on various components of the Earth system are explored. The main driver of climate change in the Earth system are greenhouse gas emissions, which are in turn driven by energy consumption from a growing population. For better understanding of interconnected structure of the model and Earth system performance Figure 5 presents the trajectories of the main stocks in the baseline scenario that define the state of the ANEMI3 model.

The change in global atmospheric temperatures follows an almost linear path (red line in Figure 5), reaching a change of almost 3 degrees by the year 2100. This is due to increasing CO2 levels, which start at an atmospheric concentration of 339 ppm and rise to 650 ppm. This corresponds to an increase of 1.9 times. The ANEMI3 model was run with the emissions scenarios for the greenhouse gases of carbon dioxide, methane, nitrogen dioxide, and chlorofluorocarbons from the fifth assessment report of the IPCC in order to compare the resulting temperature changes from the different RCP scenarios [10].

Each of the RCP scenarios represents a different socioeconomic pathway for greenhouse gas emissions and are defined by the total radiative forcing on the climate system at the end of the century. For example, RCP4.5 represents a socioeconomic pathway for emissions resulting in a total radiative forcing of $4.5W/m^2$ by the year 2100. The socioeconomic pathways embedded in each RCP scenario contain projections of population, GDP, energy production, and land use. Comparing the differences in global surface temperatures projected from the ANEMI3 baseline to those projected from the RCPs allows for a much more general comparison of where the over socioeconomic pathway of ANEMI stands.

The change in global surface temperatures resulting from running the ANEMI3 model with the RCP scenarios, is shown in Figure 6. The ANEMI3 results are found to be within what is projected with the RCP scenarios, between those of RCP6 (2.6°C by 2100) and RCP8.5 (4.3°C by 2100) corresponding to a 2.7°C temperature change by the year 2100. Comparing the CO₂ concentrations of the RCP scenarios to that of the ANEMI3 model also shows a similar result, with a very close trajectory to RCP6. This indicates that the overall socioeconomic pathway of the ANEMI3 baseline run is between one that is medium to high in terms of emissions with some climate change mitigation present.

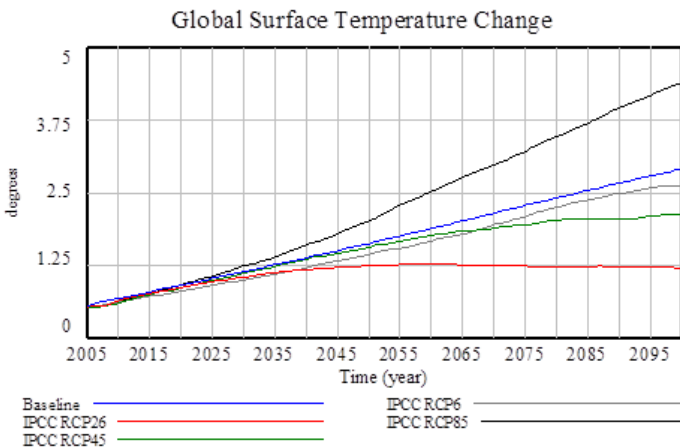


Figure 6: Global surface temperature change comparison between ANEMI3 baseline and ANEMI3 running with the RCP scenario GHG emissions

In this section the impacts of climate change on various components of the Earth system are explored. The main driver of climate change in the Earth system are greenhouse gas emissions, which are in turn driven by energy consumption from a growing population. In order to examine the range of global impacts due to climate change in the model, the RCP emissions scenarios are used and compared to the ANEMI3 baseline. This will allow for a range of climate change effects from changes in global surface temperature and precipitation to be examined.

Global surface temperature changes resulting from the RCP greenhouse gas emission scenarios are shown in Figure 6. The resulting range of global surface temperature change is between 2 to 4.4 degrees by the year 2100. The temperature change in the RCP2.6 scenario shows an increase in temperature until the year 2060, after which temperatures slightly decrease. The RCP8.5 scenario is increasing almost linearly after the year 2045 until the year 2100. The changes in global surface temperatures are used in the hydrologic cycle of the ANEMI3 model to drive changes in precipitation amounts for rainfall and snowfall, as well as evapotranspiration and available surface water (Figure 7).

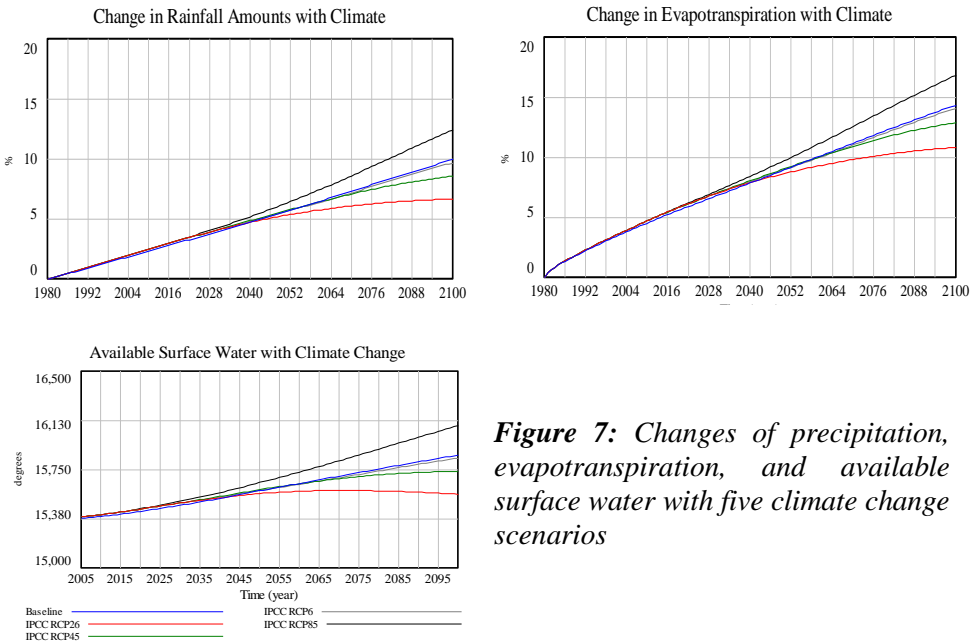


Figure 7: Changes of precipitation, evapotranspiration, and available surface water with five climate change scenarios

Increases in global surface temperatures result in changes in precipitation amounts ranging from 11 to 16.5%, with the largest changes occurring for the RCP8.5 scenario. This is due to reduced amounts of snowfall on the land surface, as well as increase in ocean evaporation and evapotranspiration. Evapotranspiration increases between 7 and 13% as a result of increase in surface temperatures.

The combined effect results in more available surface water from increase in streamflow ranging from 15,602 to 16,000 km³/year by 2100 up from the initial value of 15,240 km³/year. In the case of RCP2.6 the amount of available surface water decreases slightly after the year 2070 when the climate change signal is not as strong, however global surface temperature is still increasing slightly at this point (Figure 6). This is due to human consumption having a negative effect on available surface water, although the influence of climate on a global scale has a larger impact on the net result.

The effect of climate change on the net arable land is shown in Figure 8a. Overall, all climate change scenarios have a positive effect on net arable land, with an increase ranging from 0.5 to 0.8 billion hectares. This is because of increased arable land through conversion of boreal forests to agriculture as temperature increases (Figure 8b), along with the impacts of sea level rise on agricultural land (Figure 8c).

Although sea level rise removes arable land from the net value as agricultural areas become inundated, the effect of utilizing new potentially arable land as a result of warmer climates in northerly regions is dominating. The land yield rates affect the amount of food that is produced from the net amount of arable land in the model (Figure 8d). In all climate change scenarios, land yield is reduced significantly via increase in global surface temperature as a result of heat stress.

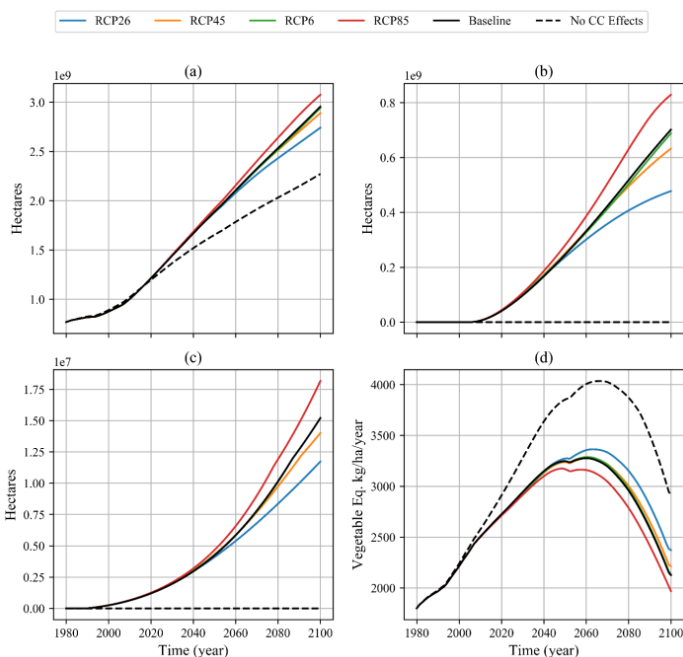


Figure 8: Effect of climate change on (a) net arable land and factors affecting food production including (b) increase in arable land through boreal forest conversion, (c) impacted agricultural land by the sea level rise, and (d) land yield.

The net effect of climate change on food production including changes in net arable land from sea level rise and arable land expansion, and land yield is shown in Figure 9. Considering all of the climate change effects included in the ANEMI3 model on food production, the result is a net decrease in food production corresponding to a maximum of 9% when comparing the RCP8.5 scenario to the scenario with no climate change effects applied.

Climate change effects on land yield and net arable land balance themselves to a degree, but in this case the effects of reduced land yield are slightly stronger. It should be noted that there are uncertainties, spatial variations, and climate change effects that are not considered here. The food production in ANEMI3 overtime shows a behaviour mode of overshoot and collapse in all scenarios.

Economic impact of climate change and its effect on global economic output is represented by the climate damage function in the ANEMI3

model, shown in Figure 10. The climate damage multiplier (functions in Figure 10) for representing the impact on economic output varies from 1 (no climate impact) in 1980 to a range between 0.994 and 0.981 for RCP2.6 and RCP8.5 climate scenarios in 2100, respectively.

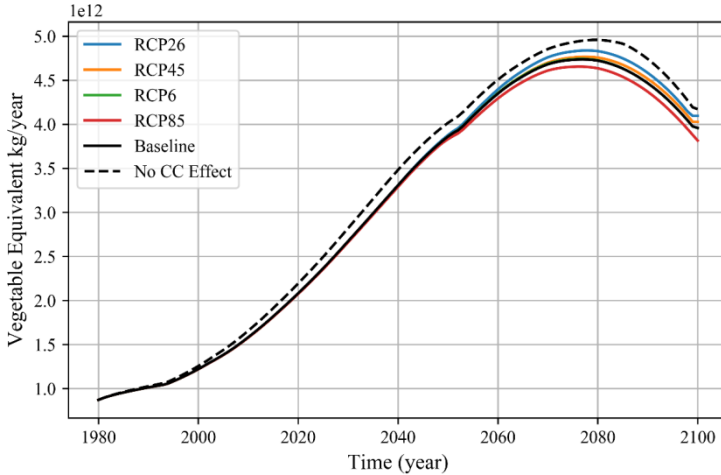


Figure 9: Net effect of climate change on food production including the effects of changes in net arable land and land yields.

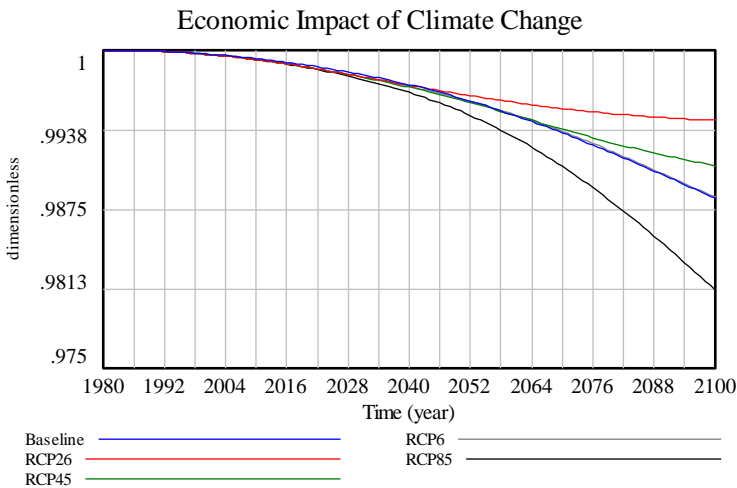


Figure 10: Climate damage functions.

This represents almost a 2% reduction in global economic output per year, which corresponds to a value of 7.6 trillion 1980 US\$ for the RCP8.5

scenario. Under the RCP2.6 scenario, climate damages appear to level off by the year 2100, however in the case of RCP8.5 the negative slope is increasing. The baseline scenario follows a pathway that is almost identical to RCP6. This is due to the temperature changes being nearly the same between the ANEMI baseline and RCP6 scenario.

4. CONCLUSIONS

Milankovitch cycles provide a strong framework for understanding long-term changes in Earth's climate. They cannot account for the current period of rapid warming Earth has experienced since the pre-Industrial period (the period between 1850 and 1900), and particularly since the mid-20th Century. Milankovitch cycles operate on long time scales, ranging from tens of thousands to hundreds of thousands of years. However, Milankovitch cycles are one important factor that contributes to climate change, both past and present.

Presented work is based on the global assessment model ANEMI [1, 2, 3] which is using as the main driver of climate change the greenhouse gas emissions, which are in turn driven by energy consumption from a growing population. Set of simulation experiments with the model confirms that climate plays an important role in the performance of Earth system.

The future integration of long term climate change impacts (Milankovitch cycles) and short term drivers (green house gasses emissions) will provide deeper understanding of the climate impacts on global change and guide future mitigation and adaptation actions.

Acknowledgments

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STRATEGIES FOR URBAN WATER MANAGEMENT AS A PART OF INTEGRATED BLUE GREEN SOLUTIONS (BGS) UNDER CLIMATE CHANGES UNCERTAINTIES

ČEDO MAKSIMOVIĆ¹ and ANA MIJIĆ¹

¹*Imperial College London, Department of Civil and Environmental Engineering, Imperial College Rd., London SW7 2AZ, UK,*

E-mail: c.maksimovic@imperial.ac.uk

ana.mijic@imperial.ac.uk

Abstract. The Blue Green Solutions (BGS) concept has been developed at Imperial College London over the last 10 years of research on the integrated urban water management. Building on sustainability approaches such as Sustainable Urban Drainage Systems and Nature Based Solutions, the BGS offers a broader view of the role of green infrastructure within urban water system and emphasises its role both in the context of integration between the traditional grey infrastructure, but also other urban systems such as planning and energy. We argue that by developing urban interventions using BGS thinking we can maximise the performance of BGS solutions by monitoring their performance and integrating them with real-time control systems (e.g., green roofs) and utilising their potential for resources recycling (e.g., local wastewater treatment plants). Adaptive planning approaches developed can provide a methodology for decision-makers to plan across long-time horizons focused on flexibility and cost-effectiveness, where BGS have a significant role in providing the additional surface water attenuation and storage, as well as other ecosystem service. Finally, BGS have a significant role at an urban catchment scale in improving in-river water quality, which is particularly significant if the environmental parameters are to become key indicators for future infrastructure planning to achieve sustainable development.

Key words: Blue Green Solutions (BGS), Urban water management, Climate change, Integrated system, Deep uncertainty

INTRODUCTION

Milanković's theory on long term succession of cold and warm periods on Earth is much more known than his "humble" work on designing civil engineering structures and systems, particularly elements of what is known today as the Urban Water System (UWS), which he practiced throughout his professional career. This paper gives an overview of strategies for development of UWS so that they become "more fit for the future". We address the UWS challenge to sustain strong impact of anthropogenic factors of climate change, which is known to have high level of uncertainty [1].

Contrary to traditional approaches in dealing with climate change adaptation (CCA) and disaster risk reduction (DRR), which usually deal with a single aspect of the process such as rainfall, runoff, water supply, wastewater treatment or water quality, our work so far demonstrated how a higher level of integrated solutions can be introduced by putting together the results of individual, small scale research under a common "umbrella" of integrated solutions, either at the level of Integrated Urban Water Management (IUWM) or even more interactive (nexus) system. The nexus thinking expands the IUWM concept to include other urban infrastructure (energy, green spaces, waste) and other ecosystem services (ESS). This integration is done through developing the "building blocks" of systemic integrated process of planning Blue Green Solutions (BGS).

We have developed this thinking, inter alia, through PhD research projects carried out at the Imperial College London under the supervision of the authors [2]–[4]. In this way, we are gradually creating a system which will address the most striking threats the present and the future urban dweller endures, such as aggravated impacts of weather extremes impacting human health and wellbeing. These impacts include urban heat island (UHI) effect, increased risk of surface flooding at both the local and regional scales [5], [6], severe drought (water shortage), loss of biodiversity and alike. Uncertainty is affecting not only our engineering solutions but also a range of socio-economic aspects [7]. Future systems will be based on strong interaction of innovative Blue Green Solutions (BGS) combined with the existing grey infrastructure to improve sustainability of cities and the wellbeing of their inhabitants through both direct benefits and co-benefits at both local and regional scale.

This paper is divided into three sections. We first introduce the overall concept of BGS and then focus on an example of our work on the green roof modelling and performance assessment. We conclude the paper with a discussion on integrated management of urban catchments, both from the perspective of adaptive planning and the role of BGS in managing the quality of urban rivers.

BLUE GREEN SOLUTIONS IN THE NUTSHELL

Historic development – predecessors of BGS

The concept of Blue Green Solutions (BGS) is developed within the EU project Blue Green Dream (BGD, www.bgd.org.uk) at Imperial College London (ICL) under the coordination of the authors of this paper. It calls for rethinking existing ways of planning, designing, constructing, operating and maintaining urban water systems (blue assets), urban vegetated areas (green assets, biomass production), buildings, energy, air quality, biodiversity, urban ESS and city behaviour under climate extremes, not as separate systems but in their combinations [8]. The innovative advantage of this method is the fact that interactions between components of urban categories, including ESS, are identified and quantified, thus enabling the planning/design team to optimise a project as a whole, based on quantitative analysis of these interactions. This has direct implications on sustainability, CCA and resilience, cost-efficiency and urban life quality, creating “healthy city for happy people”.

Although broader in coverage and paradigm, BGS concept has some similarities with the Nature Based Solutions (NBS), which originates from thinking about natural environment (forests, grasslands, wetlands etc.) as an engineering solution that provides ESS [9]. Depending on the origin and development of its implementation, NBS terminology is often linked to its “predecessors” and the aspect of functions and natural processes it covers. The scientific and professional community dealing with urban drainage and urban flood management identifies its evolutions from the early implementation of Low Impact Developments (LIDs) used in USA and Europe [10] and Sustainable Urban Drainage Systems (SUDS) originating in UK [11]. These concepts are further broadened in Australia to Water Sensitive Urban Design (WSUD) practices [12] and most recently in China as Sponge Cities (CS) concept [13]. This historic development is presented in Fig 1. Its latest expansion to include other

urban components: energy, transportation, vegetated areas, ESS, pollution and natural and anthropogenic disasters reduction and socio-economic aspects brings us to the BGS paradigm.

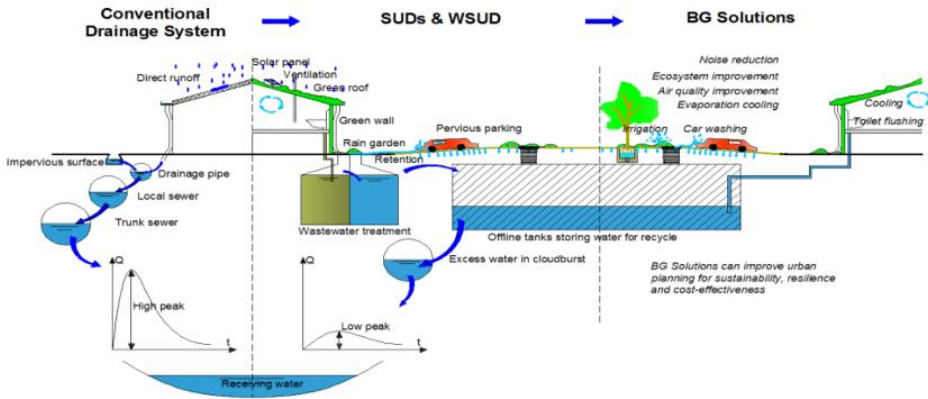


Figure 1: Historic developments of urban drainage leading to Blue Green Solutions

BGS paradigm and implementation potential

Implementation of the innovative integrated BGS requires two important changes to take place, which neither happen overnight nor spontaneously. Firstly, all big urban issues of modern days, caused by: (a) natural disasters (floods, droughts, weather extremes, etc.), (b) anthropogenic impacts (water, air and soil pollution, noise, vibration, urban heat islands, etc), (c) poor performance of technical systems (low energy efficiency, big water losses), (d) socio-economical (including gender) issues (all of which are affecting human health and wellbeing) can be converted to development and business opportunities as shown in Fig. 2. Secondly, the current compartmentalised (silo based) planning methodology needs to be replaced by systemic BGS method that proposes BGS-based integrated planning at a systems level [8]. Inter alia, BGS planning methodology [8] provides a road map towards converting major urban infrastructure and environmental issues into development and business opportunities while, at the same time, reducing negative CC impacts by providing co-benefits such as new water resources from rainwater harvesting, greywater and wastewater recycling. For example, as presented later in the paper, BGS are designed to tackle the issues of “too much water” (urban flooding) and river water pollution, supported by advanced management of SUDS elements and urban flood prediction (Fig. 3).

Finally, the BGS concept is used to address water scarcity (droughts) problem by providing “missing water” through rain-, greywater and treated effluent recycling, transferring water stressed regions into lively lush urban environments.

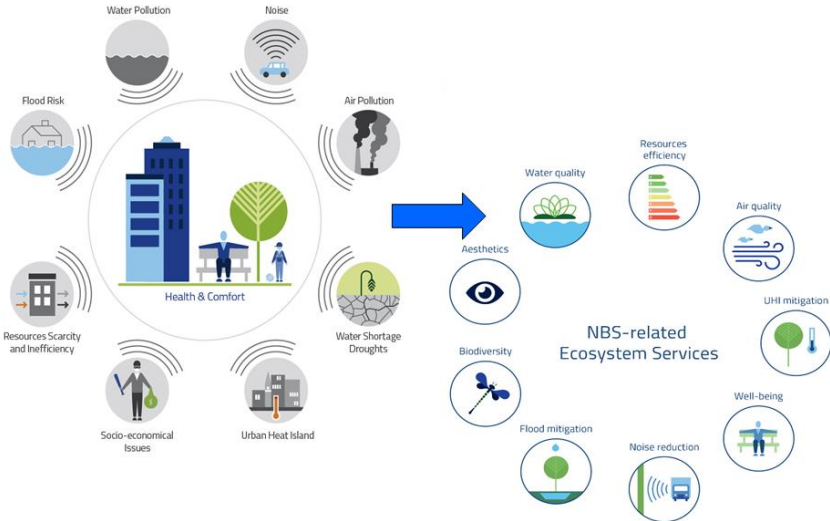


Figure 2: Addressing major urban infrastructure and environmental issues by converting them into developments and business opportunities

EXAMPLE APPLICATIONS OF BGS

Advances in implementation of BGS cannot simply rely on the current “wisdom”. They require an upgrade of reliability (reduction of uncertainty) caused by CC by prudent implementation of innovative technological solutions, next generation of physically based and integrated water models and advanced management. Examples presented below (Figs. 3-5) are based on several of these technologies. The BGS planning promotes implementation of SUDS including green roofs, vegetated swales and biofilters for improving surface runoff quality, reducing volume and peak flow of surface runoff. Successful implementation of integrated BGS strongly depends on the quality and robustness of its components. We demonstrate this by presenting results of research on hydrodynamic/hydrologic performance of a green roof, an element of a multi-functional roof garden. Results presented here are obtained by a one-dimensional water and energy balance green roof model which was developed by [2] to predict runoff from green roofs by modelling soil moisture changes within the substrate layer [14] and

simulate temperatures of foliage and the substrate surface. Sample results of the retention potential modelling for three experimental plots are presented in Fig. 3. The main results demonstrate that three installed green roofs (schematics shown at the bottom right in Fig. 3) can significantly reduce the volume of rainwater runoff, attenuate the peak flow and delay the peak time, especially for the rainfall events of small return period (1-2 years). However, this efficiency reduces for the events of longer return period (say 5-10 years). To deal with the residual runoff, however, more advanced tools are needed.

The advancement in BGS operation could be achieved by deploying advanced urban flood prediction techniques [15], [16] or using a combination of several technologies (Fig. 4). These include fine scale, real time spatial distribution of rainfall obtained by X-Band radars and calibrated in real time by the network of rain gauges, coupled with real time prediction of spatially distributed rainfall using Kalman filtering technique [17] and hybrid modelling of fine scale urban flood predictions [18]. Using these advanced near-real time forecasts provides the scientific basis for development of “smart” green roof and rainwater harvesting systems with inflow control and optimal storage operation [19].

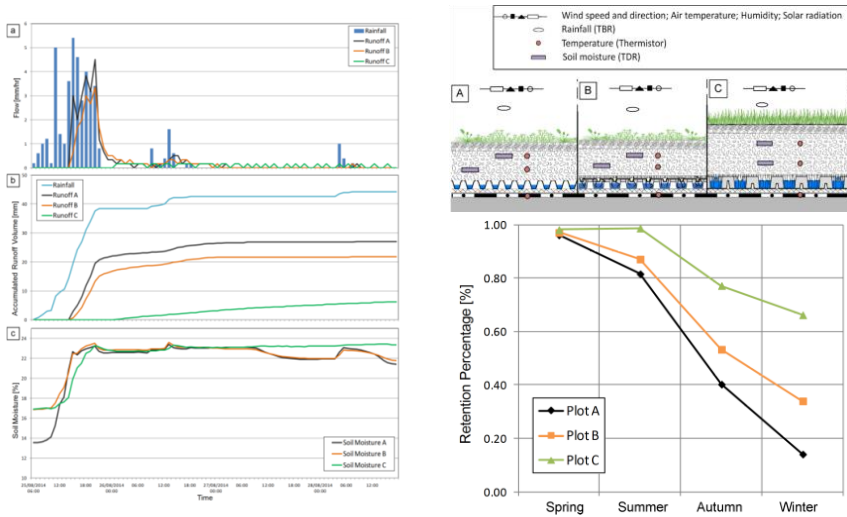


Figure 3: The schematic of the experimental green roof plots. (left): (a) Runoff and runoff profile (b) accumulated rainfall and runoff profile (c) soil moisture of three green roofs for a group of three events started at 2014/08/25, 2014/08/26 and 2014/08/28, (right top) The averaged runoff volume retention (%) of ICL green roofs for all seasons (right bottom)

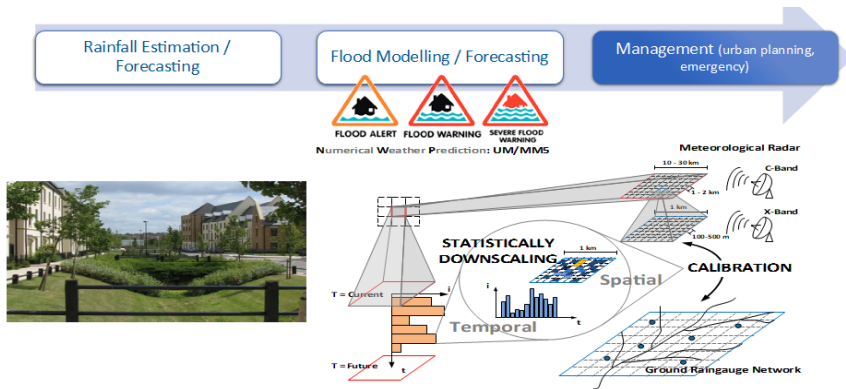


Figure 4: An example of integrated BGS implementation in advanced urban flood mitigation by combining SUDS (left) with advanced urban flood prediction and management (right)

Finally, the future on urban water systems in the areas suffering from either permanent or seasonal water shortage and scarcity, such as California droughts [20], will strongly depend on provision of additional non-conventional water resources. Such opportunity is created by water recycling and use of treated greywater and wastewater effluents. Advanced technology which contains BGS elements (aquatic plants and biofilm, see Fig. 5) is included in EU H2020 project euPOLIS as presented by I. Kenyeres (2018) [29] and [30]. In addition to providing potential for reusing treated effluent, the proprietary Biomakery (MNR) technology enables recycling of all products of the wastewater treatment plant (WWTP) process as shown in Fig. 5. Treated effluent, as one of the WWTP by-products, is a precious resource which, inter alia, can be used for irrigation of green spaces. If nutrients are preserved, such as in the secondary treatment phase, they can be used as a fertiliser, aligned with principles of circular economy in water and waste management [21].

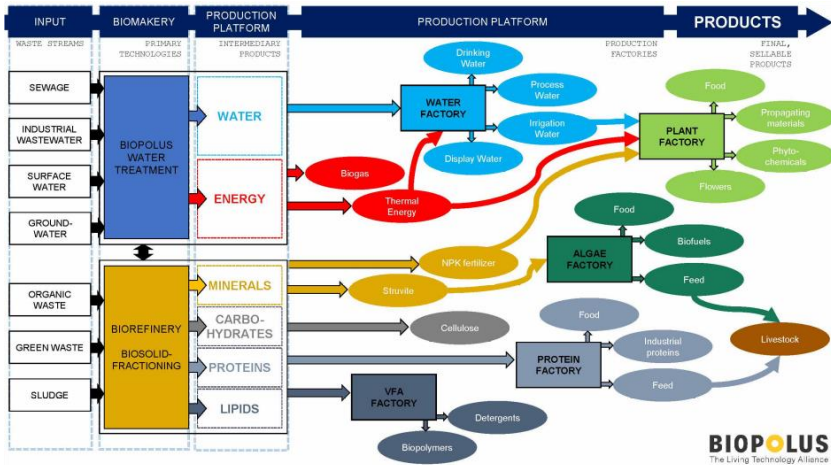


Figure 5: Multi-purpose potential of using by-products of wastewater solid waste treatment (Biopolus concept)

BGS IN THE CONTEXT OF INTEGRATED MANAGEMENT AND ADAPTIVE PLANNING

The BGS concept is also relevant from perspectives of integrated water management and adaptive planning. We argue that decisions on the future planning of water systems by combining grey infrastructure and BGS should be: (i) supported by integrated modelling to propagate the BGS benefits across the system as a whole, and (ii) developed with principles of decision making under deep uncertainty.

Adaptive planning of BGS under deep uncertainty

The concept of adaptive planning and decision making under deep uncertainty (DMDU) challenges the traditional “predict and optimise” approach and suggests that by accounting for a range of possible futures by selecting drivers of change (e.g., increase in rainfall depth and intensity) we can develop urban drainage solutions that enable flexibility in design regardless of highly uncertain future conditions [1]. In our research, we have applied the DMDU concept to develop an Adaptation Tipping Points (ATP) approach for integration of BGS with grey infrastructure solutions, considering the impacts of increase in both depth

and intensity on an urban drainage system performance [22]. The ATP approach enabled us to develop no-regret options, with adaptation pathways representing a set of interventions that can be incrementally implemented as the need for them arises due to increased pressure on the drainage system.

Results presented in the form of adaptation pathways (Fig. 6) have showed that BGS act as complementary options for longer-term adaptation strategies for surface water management alongside an increase in system storage. The ATP analysis need to be complemented by the cost-benefit assessment of individual pathways, for which the developed real options method that accounts for multiple benefits of BGS can be applied [23]. The economic analysis has shown that the key decision on the financial performance of proposed adaptation pathways will depend on the order in which options are implemented. The ATP approach supported by cost-benefit analysis provide a powerful set of tools for decision-makers to include BGS into the future planning of urban water systems under a range of climate change scenarios.

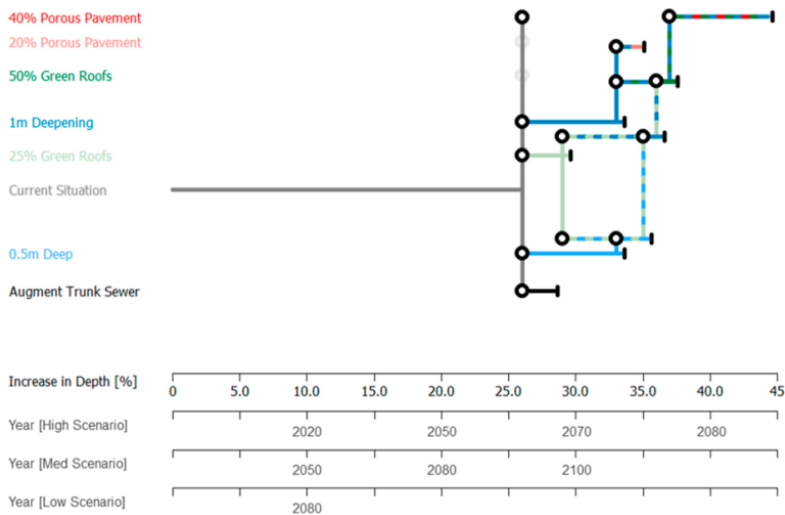


Figure 6: Adaptation pathways for a combination of grey infrastructure and BGS. Adapted from [22].

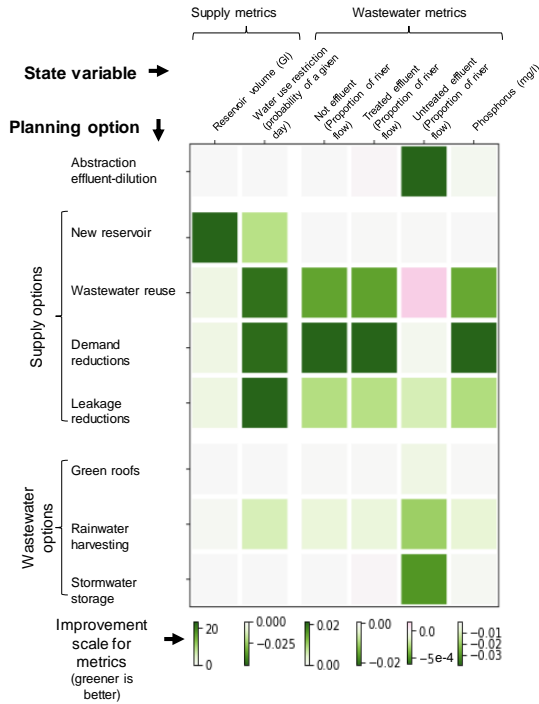


Figure 7: Comparison of water management options with respect to absolute change in various state variables averaged over the period between 1903–2018; greener indicates a greater improvement while more pink indicates a decrease in performance. Adapted from [24].

BGS within integrated urban water management

Previous examples have emphasised the role of BGS for surface water management; however, it is important to recognise and quantify their role in providing multiple ESS [25]–[27] and how they interact with wider urban water system [24]. The integration of urban planning and BGS with water management is important from the perspective of ESS provision, and these analyses could be done using the developed systems-based Urban Planning Sustainability Framework (UPSUF) [27]. The framework links design solutions and planning system process with a range of possible evaluation tools that can be used to evaluate impact of new developments on a range of ESS and the level of benefits (net-gain) achieved by the adoption of BGS such as urban parks and green roofs.

Evaluation of the role of BGS within a whole urban water system is particularly important if we want to evaluate the impacts of land use and water infrastructure planning options on the in-river water quality. To be able to do this at a whole-water systems level, we have developed CityWat, a flexible software that can model the integrated urban water cycle at a wide range of scales to suit the users' needs [24]. Performed analysis using London as a case study (Fig. 7) emphasised the important role of BGS (e.g., green roofs and rainwater harvesting) in providing benefits across both water supply and wastewater systems, with ultimate positive impact on in-river water quality measured by the level of untreated effluent as proportion of river flow. This is particularly important for smaller rivers that have lower dilution capacity and whole quality status could be more easily changed due to any additional stresses of the system such as current COVID-19 pandemic [28].

CONCLUSIONS

The paper presented the concept of BGS (Blue Green Solutions) in combination with integrated water management and adaptive planning and its potential application in CCA (Climate Change) adaptation of urban environment. Important aspect of reducing uncertainty in resilience to CC is to increase reliability and accuracy of individual components of integrated solution. An example presented here demonstrates that the carefully planned experimental tests reveal reliable data on green roofs and surface flood reduction potential dependence on its geometry and substrate composition, which can be converted into simple robust design criteria thus reducing operational management uncertainty with respect to future CC.

We believe that the future of urban water management is in holistic, systems thinking, which is based on the principle of integration, both with respect of BGS and grey infrastructure, but also how we evaluate the impact of BGS solutions at a range of scales and how we use the state-of-the-art data and real-time algorithms to improve their long-term performance and adaptability.

Acknowledgements

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Part V: Influence of Milanković's legacy

MILUTIN MILANKOVIĆ'S OPUS AS A TOPIC OF SCIENTOMETRIC REASEARCH

STELA FILIPI MATUTINOVIĆ

*Association "Milutin Milanković", Pop Lukina 1 B, 11000 Belgrade,
Serbia*

E-mail: stela.filipi1@gmail.com

Abstract. Revue of Milutin Milanković's opus studied in scientometric literature show that his theory is considered as a fundamental scientific achievement. Bibliometric analysis of his opus was performed in citation databases Web of Science and Scopus, and in databases searched by search engines Google Scholar and Microsoft Academic. Numbers of retrieved citations in result lists from those databases are different, between 440 and 2444, depending on their coverage. Search for his citations and of works that have his name in descriptors and not in reference list showed that there was much more mentioning of his name than explicit citations of his work. In Web of Science 1992-2019, 25% of records mention his name in title, key word or abstract and not in reference list, and in Scopus 1996-2019 there were 55% such records. This finding is in concordance with the fact that his name became an eponym, present in printed and online encyclopaedia, textbooks, dictionaries, websites, blogs. His name is incorporated in the scientific language, showing that his scientific contribution is widely recognized.

Key words: Scientometrics, Milutin Milanković, Bibliometric indicators, Citedness, Eponym

1. INTRODUCTION

Milutin Milanković is a great name in world science. His biography and explanation of terms that bear his name is present in encyclopaedias, textbooks, histories of science. For example, Encyclopaedia Britannica lists Milanković's biography in the GEOSCIENTISTS group, which contains a total of 245 biographies of scientists from all countries and all times. From the freely available online encyclopaedias "Wikipedia", which create volunteers from around the world in 66 languages, 52

Wikipedia contain extensive or less extensive articles on Milutin Milanković and his cycles. Term Milanković's cycles exist on Wikipedia's list of the most important concepts in all areas that every Wikipedia in a unique language should include. The list is planned to contain 1100 scientists and inventors from all countries and all times, and Milutin Milanković is one of them.

The result of many years of dedicated work on a scientific problem that he himself chose was a theory that now bears his name. Since he has accepted the notion formulated by *Kant* that in every natural science the amount of real science is equal to amount of mathematics in it, he would probably be interested in scientometric studies, and happy to learn that his opus is a subject of some of them.

In twentieth century science became a subject of research with quantitative measurement, used to describe and explain the complex system of scientific knowledge, its structure and development. Since publications were the main output of science, the discipline that evolved first was bibliometrics. Alain Pritchard defined bibliometrics as the application of mathematical and statistical methods to books and other media transmitting scientific information [Pritchard, A., 1969]. Empirical data collected on authors and publications from different disciplines, countries and periods show the existence of laws of distribution of bibliometric indicators: Lotka's law of Scientific Productivity (authors publishing in a certain discipline); Bradford's law of scattering (of articles in journals); Zipf's Law of Word Occurrence (ranking of word frequency in texts) and Garfield's law of concentration (of relevant information in a few core journals and long "tail" of less relevant ones). In the late 1980s, those bibliometric laws were proven to be mathematically equivalent. They belong to the type of statistical distribution characteristic for complex systems and social phenomena, where there are small numbers of the highly productive holders of some phenomena and large number of less productive ones [Chen, J.S., Leimkuhler, F., 1986].

Nalimov and Mulchenko were the first authors to define scientometrics as a method of quantitative research of development of science as an information process [Nalimov, V, Mulchenko, B., 1971]. Subjects of research for scientometrics are individual scientific documents, references (citations), authors, institutions, scientific journals, and analysis of the development of certain scientific disciplines in the whole or in certain

regions of the world. Basic postulate of scientometrics is that the only credible indicators for the scientific contribution of a scientist by his colleagues are: large number of citations in scientific literature which certify the use of his results, citation context analysis, and the occurrence of eponym – professional terms containing the name of the scientist [Gläser, J., Laudel, G., 2001].

2. CITATIONS AS A SOURCE OF INFORMATION

Citations are the best available approximation of the impact produced by a scientific publication. They indicate the transfer of information from one scientific work to the other. According to sociologist of science Robert Merton, citations have dual function – cognitive and moral [Merton, R., 1979]. The cognitive function is manifested by linking new knowledge to the history of science by sending readers to the sources of information that they can use in their work, and the moral function is to return the intellectual debts in the only possible way. Derek de Solla Price, “father” of scientometrics, in his famous book "Little Science, Big Science" divided the development of science in two periods: period of "small" science, i.e. science which is dominated by works of individual scientists, lasting until the fifties of the twentieth century, and the period of "big" science, dominated by the works of entire teams of scientists [De Solla Price, D.J., 1965]. In the period of "small" science, the number of active scientists and their works is much smaller [Marx, W. et al., 2010]. Therefore, it is much less likely for these works to be cited.

Eugene Garfield, founder of the Institute for scientific Information in 1960 and author of the bibliometric law of concentration, was the first to promote citations as the best source of information about the links between scientific documents that show the flow of information through the corpus of science. His intention was to enable scientists to easily find documents relevant to their work by searching for the citations of an older document relevant for the problem they were interested in. In 1963 he started publishing Science Citation Index, which covered the core journals in natural sciences, chosen according to their impact factor calculated as the average number of citations the article published in them gained two years after its publication. Citation indexes were very soon recognised as a rich source of information about the structure of science by sociologists and historians of science, and scientometric studies heavily used them. It is interesting to mention that the idea of ranking results according to

number and importance of links they have by search engine Google is based on the same principle as Garfield's idea of ranking journals according to citations they get [Baykoucheva, S., 2019].

For decades the only citation indexes were produced by Institute for Scientific Information, but now there are other databases that include citations, as Scopus launched by Elsevier from 2004, and search engines like Google Scholar and Microsoft Academic. Their coverage, transparency of data gathering and processing and openness is different. Bibliographic databases Web of Science (the successor of Science Citation Index) and Scopus are available only for subscribed users and are very expensive. Microsoft Academic and Google Scholar are freely available for registered users. Web of Science coverage is completely transparent from 1900 onwards. Scopus is less transparent because it is constantly adding older publications. Google Scholar's and Microsoft Academic's coverage are not precisely defined because they are not bibliographic databases produced by a publisher with defined selection policy for coverage, but academic search engines, collecting information available on Internet and from publishers with whom they have contracts. Bibliographic metadata provided by them are of very different quality, because they are collected from repositories, publishers, websites, academic social media, etc. It is often the case that there are duplicate data about the same publication, collected from different sources and in different formats, so the absolute numbers collected by them are less precise. Google Scholar with about 390.000.000 records has the largest database, followed by Microsoft Academic with about 237.000.000. Web of Science and Scopus have about 60.000.000 bibliographic records. [Gusenbauer, M., 2019].

3. MILUTIN MILANKOVIC IN SCIENTOMETRIC RESEARCH

The indicator commonly used in bibliometric analyse of scientific contributions is the productivity (number of publications) of scientists for a specific period of time. Productivity of Professor Milanković is calculated according to his bibliography by Milica Indjić [Indjić, M., 1994]. The following chart shows the annual scientific and professional activity of Milutin Milanković, from 1905, when he's 26 years old and published the first work, up to 1957, when he published the last one at 78 years of age. Works that were translated or reprinted after the authors'

death were not taken into account. Literary and popular publications are not included. Three creative periods are clearly shown. The first one lasts from his ages of 26 to 37, with a total of 23 works published. The second, the most fertile period lasts from his 41 until 61 years of age. It starts at 1920, with a monograph that contained his results so far, and ends in 1941 with a monograph in German, with the synthesis of his whole life's work. In second period he published 34 works. The third period starts after the Second World War and lasts until the very end of his life. In that period, he published mainly university textbooks and articles from the history of science, assuming that his great research on astronomical theory of climate change was rounded up and that he is too old to begin anything new.

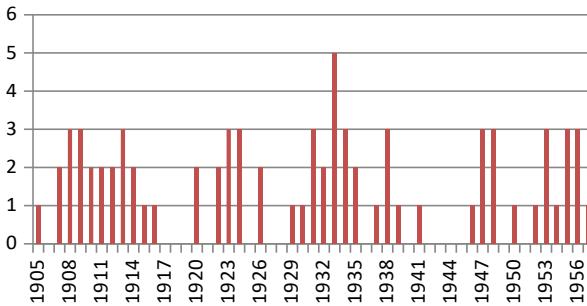


Figure 1: Number of publications annually

Table 1. Distribution of citations between publications in SCI/WoS 1928-2019

Number of citations	1	2	3	4	5	6	7	8	9	10	13	30	47	56	146	343	780
Number of publications	7	10	6	2	3	4	1	4	2	1	1	1	1	1	1	1	1

The most cited work is *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*, Belgrad, Königlich Serbische Akademie, 1941, with 780 citations, *Mathematische Klimalehre und Astronomische Theorie der Klimaschwankungen, Handbuch der Klimatologie, Bd I*, T.A. Hrsg. von W. Köppen und R. Geiger, Berlin, Gebruder Borntraeger, 1930, with 343 citations and *Théorie mathématique des phénomènes thermiques produits par la radiation solaire*, Paris, Zagreb, 1920, with 146 citations. It is interesting to notice that all three most cited publications were monographs published before the Second World War, but the number of citations that they receive is still high, showing their fundamental importance.

What Milanković is exceptional for, and especially from today's perspective of teamwork in science, is that he was the only author of all his publications. It is important to emphasize that he did work alone, but not in isolation. Milanković was aware that successful work in science is not possible without continuous monitoring of world scientific literature and without intensive communication with colleagues all over the world. To make his results discoverable and understandable to his international colleagues, he wrote his most important works in German and French, which were the main languages of communication in world science at that time. How closely he was connected to his colleagues from abroad is visible from his rich correspondence and his personal library, where he kept all the works of the authors who used and cited his works. All citations have been neatly recorded and on the list that was saved in his legacy at the Serbian Academy of Sciences and Arts. There are 110 works in which his scientific results were cited. In this regard also he was avant-garde, realizing that the citation networks are a much better system of connecting scientific literature by content than any existing classification scheme of scientific disciplines.

Different aspects of the problem of citations are increasingly being investigated, especially since the bibliometric criteria are used in the evaluation of scientific work. For our theme the most interesting is the article of Marx, Haunschild, Thor and Bornmann, dedicated to exploring the most cited publications in the literature on climate change. [Marx, W.,

et al., 2017]. Work deals with the general history of climate change research, with an emphasis on discovering the impact of greenhouse gases. The articles were collected from the database Web of Science from years 1980 to 2014, with a total of 222,060 articles, in which 10,932,050 publications were cited. Authors identified 35 publications that were most cited in the observed sample. Early works that are still much cited have been identified, for which it can be stated that they represent the intellectual roots of this discipline. It has been shown as expected that older publications are less represented in the cited literature, but that the distribution of the number of such publications by the years of publication gives a very high maximum of certain years. These maximums originate from individual early publications, which are of particular importance for the development of the discipline. The authors first extracted the cited publications published before 1971, whose number was 239,887. They then extracted those publications that were cited more than 100 times, whose number was 226. On the acquired table, the work of Milutin Milanković "Canon of insolation" was found in a thirteen place with 352 citations. Authors thoroughly analysed the first 35 publications in the list, which, according to them, are the cornerstones of modern science about the climate.

The important fact that influenced on citations of Canon is also that it is written in German, and translated to English only in 1969, as a part of Israeli program for scientific translations of important scientific publications published in the Eastern Europe, financed by National Science Foundation of USA. John Levin analysed the use of literature in geomorphology, and found that English use in scientific papers rose from 55% in 1970s to over 90% by the end of the century. There is much greater potential for the wider dissemination if the publication is in English, since it became "lingua franca" for scientists all over the world. In this article publications by Milanković are used as an example of importance of translation to English language for enhancement of communication in geomorphology [Lewin, J., 2017].

In Serbia there are a few researches that analyzed Milutin Milanković from a bibliometric perspective. The first data were published in an article by famous Serbian sociologist Vojin Milić (1922-1996), who analyzed science in Serbia as a subject of contemporary Serbian historiography. He collected data from the database Science Citation Index for years 1965-1989 for Serbian natural scientists. Milutin Milanković was the most cited

of them [Milić, V., 1993].

Serbian astronomer Milan Dimitrijević analysed citations of Milanković 1946-1990. [Dimitrijević, M., 1997] and published in 2005 the book “Serbian astronomers in Science Citation Index in the XX Century”, analysing the presence of citations for works by astronomers from years 1945 to 2000. The most cited author was Milanković with 572 citations. [Dimitrijević, M., 2005].

Publishing house Zavod za udžbenike from Belgrade published two editions of Milutin Milanković’s selected works. First edition of the book 8, published in 2008, contains article “Work of Milutin Milanković from scientometric perspective” and lists all citations his works received, present in Science Citation Index 1945-2006. [Filipi Matutinović, S., 2008]. Extended version of that article was published in 2009, in the catalogue of the exhibition about Milutin Milanković, prepared at the University Library “Svetozar Marković” in Belgrade. [Petrović, A., Filipi Matutinović S., 2009].

Eugene Garfield, creator and editor of Science Citation Index, produced special software for bibliometric research of individual authors or subjects, named HistCite. Software was used for analysis of citations present in Science Citation Index database for the period 1900-2010. HistCite collections of papers consist of works by highly productive scholars and scientists. In Garfield’s digital library available in open access on Internet, there are data for citations of 178 authors from the period of “little science”, and one of the chosen authors for presentation is Milutin Milanković [Garfield, E, 2020]. Since Garfield introduced the method of citation as a qualitative measure of academic impact, the fact that he chose Milanković as an example of important scientists whose citations matter for the history of science is very significant fact for estimation of his scientific reputation.

4. MILUTIN MILANKOVIC IN WEB OF SCIENCE, SCOPUS, GOOGLE SCHOLAR, MICROSOFT ACADEMIC AND ASTROPHYSICAL DATA SYSTEM

Bibliometric analyse of Milanković’s work was performed by analysing the results of search for citations of his works and for topic (keywords and titles) in publications containing his surname in special databases or

search engines that are available: two commercial databases – Web of Science and Scopus, and two search engines designed for academic use – Google Scholar and Microsoft Academic. The citation analysis was conducted using the “Cited reference search” feature in WoS. All citing documents and all citations to documents authored by “Milankovic M, Milankovitch M or Milankovich M” were retrieved. A complementary search was performed in WoS in order to retrieve all publications containing “Milankovic, Milankovitch or Milankovich” either in their titles, descriptors or abstracts. This should give an idea of how many citations have been omitted because his works have already been assimilated by the scientific community as common knowledge and therefore ceased to be cited directly any longer. The search was restricted to the field “Topic” (searches title, abstract, author keywords, and keywords plus), and repeated for the field “Title”. The search for citations in Scopus was performed in the “References” field. All references containing the name “Milankovic M, Milankovitch M or Milankovich M” were retrieved. On the fig. 2 is shown that WoS retrieved more citations before 1988 and that Scopus started to collect more results than Web of Science after 1996. WoS included abstracts and enabled keyword search in 1992, so it is possible only in Scopus to search for keywords containing Milankovic or Milankovitch or Milankovich before 1992.

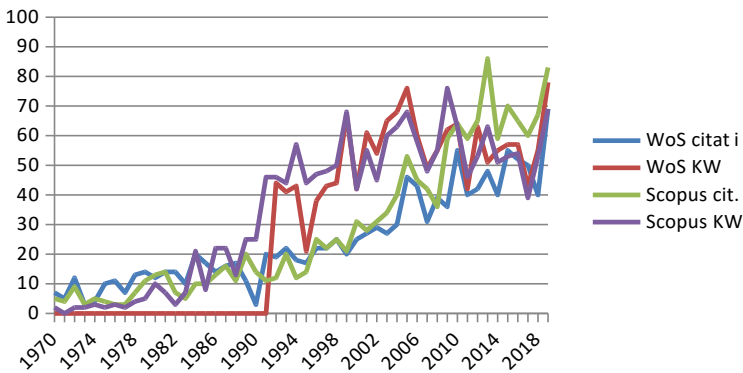


Figure 2: Number of citations and Keywords in WoS and Scopus

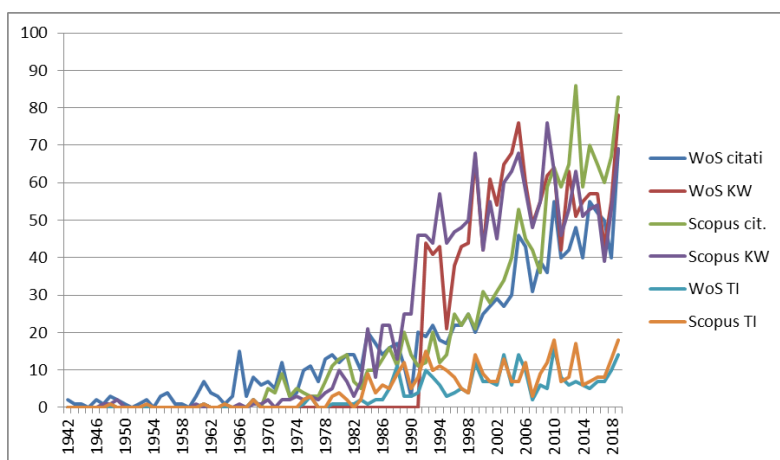


Figure 3: Citations, key words and title words in WoS and Scopus 1941-2019

Figures 2. and 3. clearly show the trend of constantly growing usage of Milanković’s works, proving that his theory is a good example of a “sleeping beauty” in science that was widely recognized more than half a century after it was first published [Van Raan, A.F.J., 2004]. The number of citations is increasing. That is characteristic only for fundamental works; usual trend is decreasing after reaching maximum in the first decade after publication. Marx founded that most of the works published at the beginning of the twentieth century were no longer cited at all after year 1960 – only works that had fundamental significance for the development of physics were cited [Marx, W. et al, 2010].

It is important to mention that citations of Milanković’s works appear in the journals with the highest impact in different research areas – geophysics, geology, climatology, astronomy, ecology and above all in multidisciplinary journals. The distribution of citing articles according to research areas in WoS and Scopus is very similar. Majority belongs to the earth and planetary sciences, important groups belong to environmental and multidisciplinary sciences, and there are also citations from physics and astronomy, engineering, mathematics, social sciences, arts and humanities, agricultural sciences, etc.

It is possible in WoS 1996-2019 to observe the distribution of the citing records between authors. There were 2730 authors citing Milanković from 1996 to 2019. Authors that cited Milanković ten or more times are: A.

Berger, M.F. Loutre, V.A. Bol'shakov, M. Crucifix, G. Lohmann, W.F. Ruddiman, W.H. Berger and P. Huybers. In Scopus the authors citing Milankovic most in the whole database are: L.A. Hinnov, A. Berger, F.J. Hilgren, A. Strasser, S. Zhang, W.H. Berger, F.J. Rodriguez-Tovar, L.J. Lourens, T.R. Naish and P.E. Olsen. Authors are from 70 countries, and more than 50 citations are from USA, Germany, Great Britain, France, China, Russia, Italy, Belgium and Canada. The leading countries in climatology research according to a bibliometric study [Haunschild, R. et al., 2016] are USA, Britain, Germany, Canada, China, France and Australia, so our results are in accordance with it. Absolute majority of citing articles in Web of Science were published in English language (98%), 1% was published in French, and a few articles were published in Russian, German and Chinese.

Search for citations was repeated in search engines Microsoft Academic, which provides data from 1981 and Google Scholar, which provides data from 1945. Microsoft Academic retrieved 440 citations and Google Scholar retrieved 2444 citations. Data obtained from academic search engines Google Scholar and Microsoft Academic returned bigger absolute numbers because those search engines get data not just from journals but also from institutional digital repositories, dissertations, conferences, books, preprints, etc. and that they contain duplicate records because no control of metadata is provided. Data from Google Scholar and Microsoft Academic were retrieved with the help of open source “Publish or Perish” tool by Ann Vil Harzing. [Harzing, A-W, 2020]

Google Scholar gives an option for authors to register and create profile, enabling them to analyse citedness of their works and search for profiles of other scientists that created profiles. We created a profile for Milutin Milanković, and the result is the following graph.

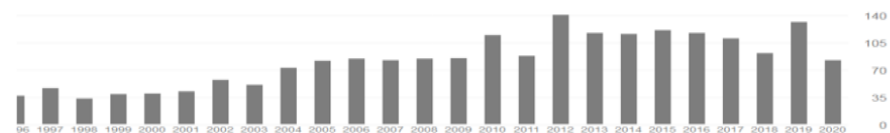


Figure 4: Citations of works by Milutin Milanković in Google Scholar

The most cited works in Google Scholar are: “Kanon der Erdbestahlung und seine Anwendung auf das Eiszeitenproblem” with 950 citations and

its edition in English with 587 citations, “Mathematische klimalehre und astronomische theorie der klimaschwankungen” with 606 citations and “Théorie mathématique des phénomènes thermiques produits par la radiation solaire” with 387 citations. “Kanon” in the result list appeared as four different publications with the same publication year, each with separate number of citations because there is no metadata control.

SAO/NASA Astrophysics Data System (ADS) - a digital library portal for researchers in astronomy and physics, operated by the Smithsonian Astrophysical Observatory (SAO) under a NASA grant, contains about 13 million records. It also enables search for citations. On 16.06.2020 in that database Milanković had 1992 citations.

The cumulative results obtained from Web of Science, Scopus, Google Scholar, Microsoft Academic and Astrophysical data system are compared in the table 2.

Table 2: Total results from used database

Database	No. citations	No. articles with keywords	Articles with title words	Citations and keywords
Web of Science 1920-2019	317	1458	255	242
Scopus 1996-2019	426	1756	352	308
Google Scholar	444	29768	1021	-
Microsoft Academic	40	1996	398	-
Astrophysical data system	992			

The first evident fact is that numbers provided by Google Scholar are much bigger. Number of citations is correct, but number of keywords is far too big and cannot be relevant for this analysis. Since it is possible to see only 1000 records for each search, it is impossible to analyse and perform cleaning of the inadequate records from the result list. It was

noticed that Google Scholar collects keywords not just from abstracts, titles and full texts, but includes in the result list publications by all authors with the surname Milankovic (including Milutin Milankovic) and a lot of duplicate records collected from different sources – from publishers, repositories, etc. So we must conclude that WoS and Scopus are for the time being the only completely relevant sources for bibliometric analysis, because they provide the exact data of how and from which sources they include data in their databases, without duplications and with correct metadata.

Data in table 2 show that the number of citations is less than the number of keywords in all four databases. Most interesting fact is that there are only less than 10% of retrieved records in WoS and Scopus mentioning Milankovic that contain both citation to some work by Milankovic and keyword or title that contain his surname: Milankovitch cycles, Milankovitch forcing, Milankovich theory, etc. When analysing the records lists retrieved as a result of three queries submitted to databases WoS and Scopus (articles citing Milankovic, articles with term Milankovic in title and articles with term Milankovic in keyword or abstract) it was observed that those lists are not overlapping. Those databases give the possibility to combine result lists of queries, so it was possible to determine the exact number of records present in all three lists. Number of mentioning Milankovic in those databases is nearly twice bigger than number of citing articles or number of articles with Milankovic in title or keywords. These results indicate that his name become an eponym.

5. EPONYMS IN SCIENCE AND MILANKOVIC

Eponyms are scientific terms formed after a person – inventor or scientist who was the first to discover or to communicate to other scientists some invention, discovery, theoretical explanation etc. Robert Merton, one of the pioneers of the sociology of science, defined eponymy as the practice of affixing the names of scientists to all or part of what they have contributed. He showed that eponymy is an important mechanism of recognizing scientific contribution. Creation of eponyms is a part of stimulation system for science development, since it gives great and long-lasting reward to scientists by their peers [Ravlić, S., 2006].

Eponyms have an important role in communication in science, because

they transfer a part of its meaning from abstract concepts to iconic scientists related to these concepts. This is very important for frequently used scientific concepts [Koshlakov, D. et al., 2019]. Eponyms are present in contemporary scientific terminology in many scientific disciplines. Webster unabridged dictionary lists about 9000 eponyms in all fields, The Eponyms dictionary index lists 13.000 eponymized persons, and there is a lot more dictionaries of eponyms for different fields.

The systematic use of eponyms can be regarded as one of the most effective reward systems in Western science. Astronomers practice to use eponyms to honor distinguished predecessors. In Milanković honor, a crater on the dark side of the Moon was given his name at the Congress of the Astronomical Union in Brighton 1970, and in 1973 the same organization decided to give his name to a crater on Mars. A celestial body in the asteroid belt, discovered by Serbian astronomers also is named after him – 1605 Milankovic.

In scientific literature eponyms serve as implied citations. True eponymy is achieved when the following conditions are met contemporaneously:

- The event in question (method, law, rule, etc.) is commonly called by its discoverer's name
- The eponym is recognized by its inclusion in the indexes of standard texts in its field
- The eponym is used as a heading in a paper or text
- The event is implicitly cited by the use of the eponym [Thomas, K.S., 1992].

Existence of eponyms in a scientific discipline is influencing the possibility to correctly determine the number of citations for a specified scientist or a theory, as the eponymized author is not cited any more with a defined bibliographic reference. His name is incorporated in the scientific language of a discipline. This phenomenon is called obliteration by incorporation and was first described in detail in Merton's article about Matthew effect in science in 1968 [Merton, R., 1968].

Eugene Garfield wrote about the phenomenon of obliteration, claiming that most scientists will not cite a source if it has been absorbed into the scientific language, since the readers are already aware of it. [Garfield, E., 1974] In his essay about the importance of not being cited he states: "An

implicit citation, made by incomplete, casual, or mere last-name reference in the text, indicates that the author assumes the reader will know that the theory, the method, or the technique referred to is part of their common working knowledge and need not be explained or verified"... That kind of uncitedness happens to "those whose work has become so well known (and presumably been previously so heavily cited) that one finds it at first tedious, then unnecessary, and finally actually gauche to cite such men at all" [Garfield, E., 1962].

In his essay about eponyms as a route to immortality, Garfield states: "Eponyms remind us that science and scholarship are the work of dedicated people. They allow us to immortalize sometimes obscure but deserving persons" [Garfield, E., 1983].

If we analyse the results of Milanković's mentioning in databases WoS and Scopus, we can see that for the period 1992-2019 there are 25% of all retrieved records in Scopus and 55% of retrieved records in WoS where his name is mentioned without citation. That is clear evidence that his work has been obliterated by incorporation since his name became an eponym. The trend of using his name as an eponym, without explicitly citing his works is evident from figure 5. The run of both curves is similar in both databases. Both the number of citing articles and articles mentioning his name without citing has gradually increased within the last 50 years according to the growth in the scientific world output.

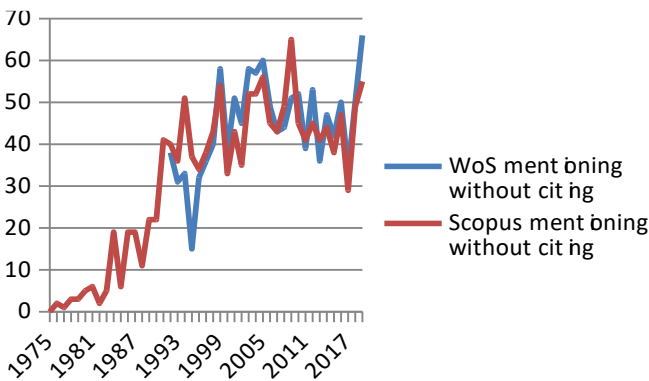


Figure 5: Records mentioning Milanković without citations

The syntagm "Milankovitch cycles" is present in textbooks, encyclopaedias and lexicons in many languages and is widely used in scientific literature. The best proof that his name is a widely used eponym

is that the definition of the word "Milankovitch" is present in the Oxford English Dictionary [Oxford University Press Lexico Dictionary, 2019]. It is also present in cosmos, since craters on the Moon and Mars and one asteroid bear his name.

6. CONCLUSION

We can conclude that Milutin Milanković achieved great international reputation. By becoming an eponym, his name will be part of the corpus of knowledge forever. This conclusion would not be so obvious if we analyze and compare just the plain numbers of citations for different authors. Citation analysis is definitely a useful tool to study the impact of the works of great scientists, but it is too restrictive, because it does not include the phenomenon of obliteration and creation and use of eponyms. We can state that Milanković achieved his life goal and built his “eternal and inviolable scientific estate”. His theory is inseparable part of scientific legacy of humankind, surpassing the boundaries of his scientific environment and boundaries of the discipline he worked in. Results of this scientometric analyse confirm his exceptional place in world science.

Acknowledgments

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R E V I E W
THE MOST IMPORTANT FINDINGS OF AMERICAN
SCIENTISTS AND ITS CONCLUSIONS IN RELATION
TO MILANKOVIĆ THEORY OF INSOLATION

VLADO MILIĆEVIĆ^{1,2}

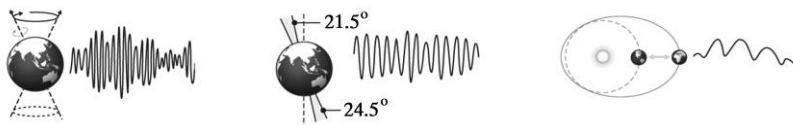
¹*3VM Geo Ltd.*

3219 Signal Hill Dr SW, Calgary, AB T2P T3H, Canada

E-mail: vladomilicevic@shaw.ca

²*Association "Milutin Milanković"*

Pop Lukina 1 B, Belgrade, Serbia



Abstract. The overview of this paper shows the most important findings and its investigations that American scientists concluded regarding Milanković cyclity of insolation. The review of these findings is shown chronologically: from eighth decade of XX century, ninth and tenth to first and end of second decade in XXI century. In the conclusion of this paper the most important result of these investigations from last half century are presented. A small number of American scientists did not recognized Milanković cyclity of insolation, basic principle of mathematical climate and climate modeling, climate changes and global warming. However, today in United States of America there are no scientific papers without data from Milanković mathematical calculation and astronomical elements, precession, obliquity, and eccentricity. Therefore, the numerous American scientists changed their view about Milanković cyclity and confirmed his mathematical calculations on Earth, Solar system and in the area of 3D observations.

Key words: Milanković cyclity of insolation, Confirmations and contributions of Milanković theory, Mathematical climate and climate modeling, Global warming and politics

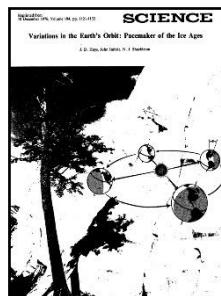
1. INTRODUCTION

American scientists were not interested in Milanković's theory of insolation for a long time (from 1920s to 1950s). Although, the territory of North America contains a lots of evidences about ice ages from the geological past, especially in Quaternary period. That was the main reason why the priority and cause of ice ages were on the side of Alpine glaciologists and geomorphologists (Germans and Italians). Until American scientists decided to collect more evidences about astronomical forces on Earth's climate. In the early 1970s Milanković calculation was examined and culminated, but for huge and very expensive project financial support was in American scientists only. American National Scientific Fond decided to organize project CLIMAP (Climate: Long-range Investigations, Mapping and Prediction) and it started in 1971. The primary and the main goal were to investigate climate changes in last 700,000 years. The final results of CLIMAP project were the astronomical elements like precession (23 and 19 ky), obliquity (41 ky) and eccentricity (100 ky) that changed the climate on Earth's in the geological past. The priorities of climate investigations were in the American scientist's hands, especially after 1970s due to CLIMAP project where their contribution to development of paleoclimatology was very important. However, they made their unscientific work and results in the frame of global warming and climate changes.

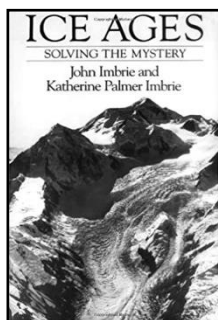
2. THE MOST IMPORTANT FINDINGS OF AMERICAN SCIENTIST UNTIL END OF EIGHTH DECADE OF XX CENTURY

When we talk about Milanković's theory of insolation, American scientists approached an interesting research path: from absolutely denying and neglecting to theory to organizing an important and large project by including wide a range of applications, to this day. The 1976 was "zero year" or "turning point" because it is the year when first paper was printed in the scientific journal "Science":

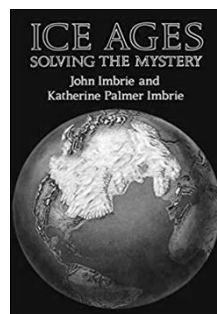
Hays, J, D, Imbrie, J, Shackleton, N, J.: 1976,
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That work was sublimation of five-year project CLIMAP. Based on this project, we have strong evidence that Milanković's cyclity of insolation and his calculation proved the existence ice ages. More details are available in the book:

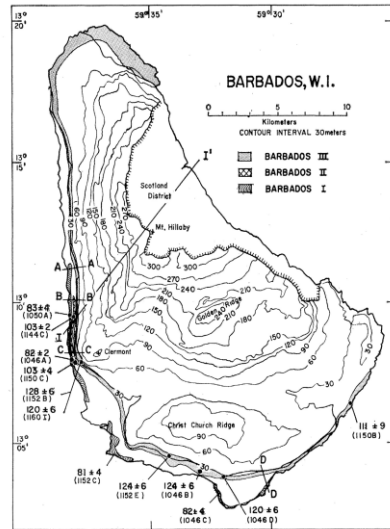
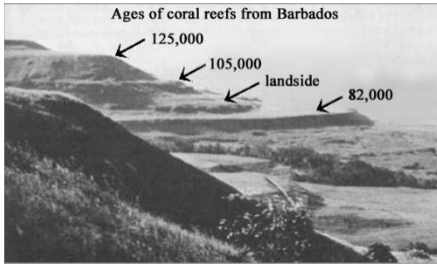


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If we want to supplement the important of 1960s and 1970s and complete American's view on Milanković's theory, we have to introduce some scientific papers from that time. Therefore, the following papers were selected: the papers are presented chronologically by decades, except in case of decades seventh and eight of XX century. Based on limitation number of paper (up to ten), we selected 10 papers per decade. We selected objective and scientific complete research papers. Consequently, leading 10 research papers are next:

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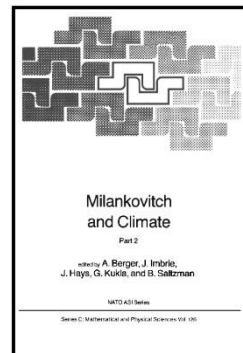
9. Vernekar, A, D.: 1972, Long-period global variations of incoming solar radiation, Meteorological Monographs, 12, Amer. Meteorol. Soc., Boston.

10. Wilson, A, T.: 1964, Origin of ice ages: an ice shelf theory for Pleistocene glaciation, Nature, 201, 147-149.

3. THE MOST IMPORTANT FINDINGS OF AMERICAN SCIENTIST IN NINTH DECADE OF XX CENTURY

From the eighth to ninth decades of XX century American scientist did not question Milanković's theory of insolation. As it was stated simply: they *deeply believed in Milanković theory*. They continued to find more evidences, but the most important conference in that time was "Milankovitch and climate" by NATO organization in Palisades (New York). In the 1982 scientists in Serbia did not understand the real intension of this conference, therefore they spoke of Milanković's theory of insolation as a successful discovery!

Milankovitch and Climate: Understanding the Response to Astronomical Forcing, 1982, (Berger, Imbrie, Hays, Kukla, Saltzman, eds.), NATO ASI Series, Ser. C, Mathematical and physical sciences, 126, November 30 – December 4, Palisades, New York.



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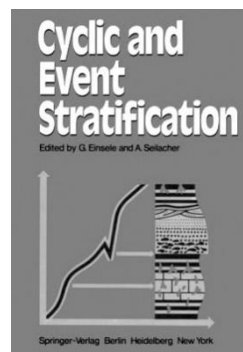
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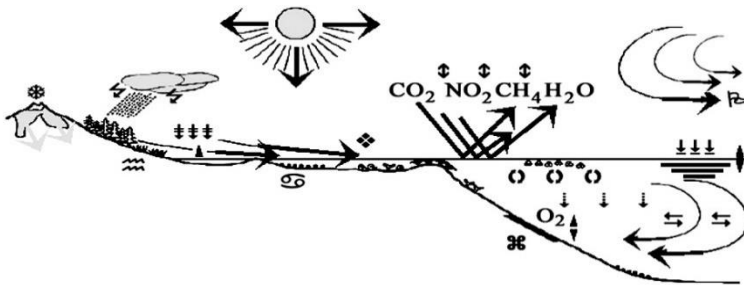
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4. THE MOST IMPORTANT FINDINGS OF AMERICAN SCIENTISTS IN TENTH DECADE OF XX CENTURY

In the last decade of XX century numerous American scientists tried to find strong cyclostratigraphy evidences in ice samples from Greenland and Antarctica boreholes. Ice samples from Greenland to 150 ky in the geological past (from last three ice ages in Würm glaciations) and samples from Antarctica to 420 ky in the geological past (from five ice ages in Riss and Würm glaciations) gave details and precise time determination. They were basic elements for time travel in deep age periods and control of Milanković cyclity in a period of Phanerozoic Eon.

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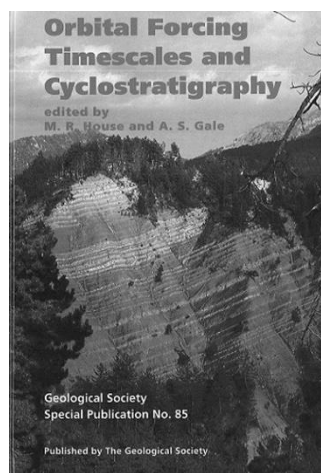
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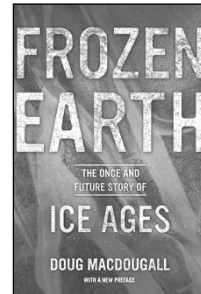
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In first decade of XXI century the interest for Milanković's cyclity of insolation was still very active. It continued on broader geological time scale called the "Milanković band" (spread time between 10 ky to 1 m.y.). During the first decade a very sudden and the wide development of Milanković's cyclity in geochronology occurred was a very important discovery for new scientific discipline - *astrochronology*.

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6. THE MOST IMPORTANT FINDINGS OF AMERICAN SCIENTIST IN SECOND DECADE OF XXI CENTURY

In second decade of XXI century an extensive applications of Milanković's theory of insolation were wider than the "Milanković band". In the framework of American scientists we can find segments from Pliocene-Pleistocene cyclostratigraphy, glacial and human's evolution to partially solve the problems from the area of astrochronology, microevolution, even history of Solar system, etc. Based on the new technology and in the current period and the time of research is expanded to the one billion year of planetary age!

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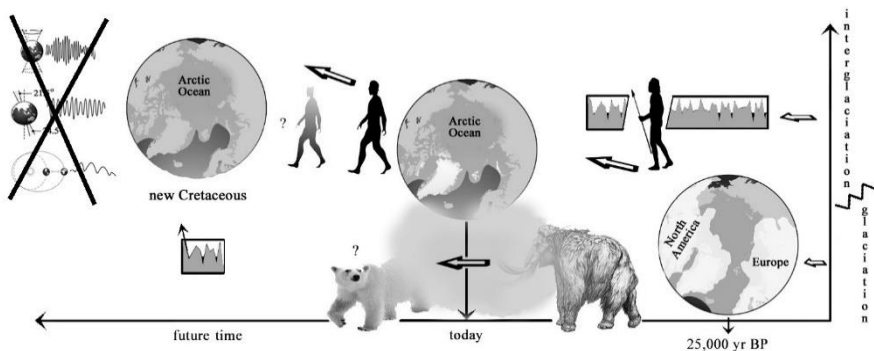
7. COMMENTS AND CONCLUSIONS

In the last century American scientists give the world significant contribution to Milanković theory of insolation. Reviews of their results are shown through the fifty selected papers, but this is only an opinion. The Nobel Peace Prize 2007 were awarded jointly to the IPCC (Intergovernmental Panel on Climate Change) and Albert (Al) Gore.

After all they were passive regarding an urgent problem of global warming.

They did not contribute to further research shown in the frame of contradictory title *struggle against climate changes*!

Struggle against climate changes is very contradictory and as stated: a) man vs Nature, b) man vs industry and development, and c) man like supernatural creature, will result in extinction of humanity (man vs man).

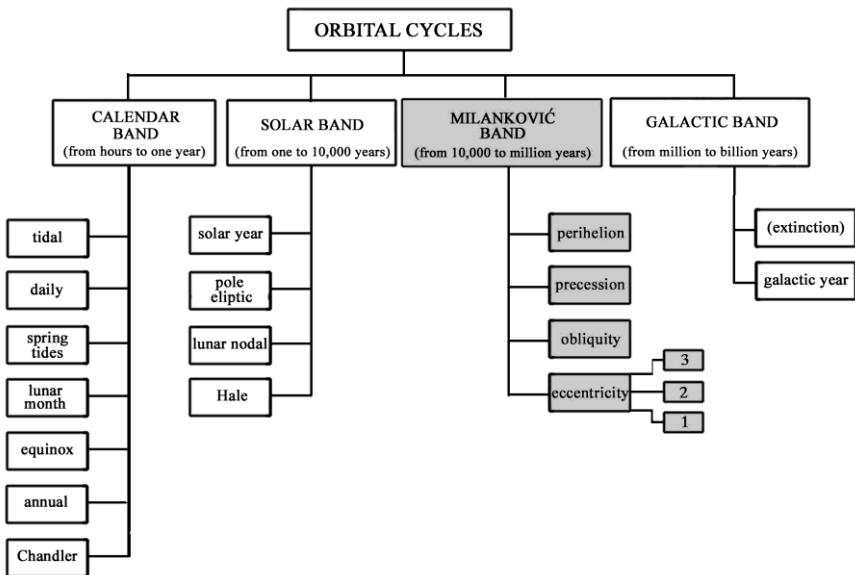


The most American scientists tried to find more evidences about Milanković's theory of insolation until eighth decade of XX century. They researched the cause of ice ages, discovered cyclity changes in Pleistocene and Pleistocene, and tried to let out their knowledge about changes in coral reefs and deep sea and ocean sediments. They were first and important marks that they wanted to work in the wide areas, older time sequences, and universality of Milanković's theory of insolation. The initial Milanković's calculations were for 600 ky only, but it was changed by first climate modeling, possibilities to continue the orbital mechanism to older formations and geological time scales, even thought to all Phanerozoic Eon.

In the frame of Milanković’s theory of insolation the most important events in eighth decade of XX century were project CLIMAP, scientific paper by Hays, Imbrie and Shackleton from 1976, and the book “Ice Ages: Solving the Mystery” by John and Katherine Palmer Imbrie. They played significant role in solving astronomical influence like “pacemaker of ice ages”.

The *cyclostratigraphy* is a new method which was discovered in ninth decade of XX century. It is stratigraphy subdiscipline for identification, characteristics, correlation, and interpretation of astronomical cyclity changes (periodic and quazi-periodic) in the stratigraphic layers with applications to geochronology and development the precise in time scale stratigraphy. There are three main cycles in the cyclostratigraphy: a) precession (P), b) obliquity (O), and c) eccentricity (E). The Milanković Frequency Band is one of the basic time factor (See Table 1).

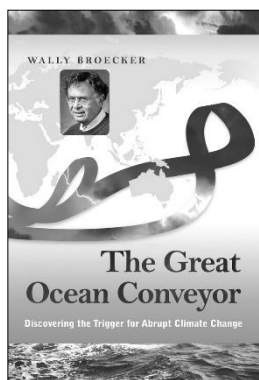
Table 1: *Orbital cyclity with basic frequencies which exert an influence on energy reaching the outer atmosphere (after House, 1995, modified by Grippo and author of this paper).*



Out of numerous American scientists-paleoclimatologists one of them was very famous, Wallace S. “Wally” Broecker (1931-2019). He was the founder of ocean conveyor and persistent scientist who tried to find strong

evidences for dangerous planetary climate changes and global warming. In his book „Fixing Climate – what past climate changes reveal about the current threat – and how to counter it” from 2008 (wrote with Robert Kunzig) they called the Milanković cyclity of insolation “Serb theory” (page 27, title three “Ice Age and the Serb Theory”. This was not an honor to one scientist, but to his people. They did not write this commonly used name “Milankovitch”, rather his proper name Milanković.

Thought many American scientific papers we can see a wide range of applications that Milanković’s cyclity of insolation can be used. We list a limited number of these applications, but we note that his theory is still open for many more.



- determination of absolute time, especially in Pliocene and Pleistocene, but in the older formations as well;
 - at cyclity calibrations;
 - estimation and duration of stratigraphic stages;
 - understanding the climate in past geological time, from today to all Phanerozoic, but in the future, too;
 - strong connection between man evolution and climate change;
 - detail informed the history of Solar system;
- cause of flood, drought, ice ages, “green house” effect, changes of sea level, monsoons, El Niño, tornadoes, etc.

Planetary problem of climate change was delayed for very short period of time by coronavirus disease (COVID-19). In the future, climate change will come back on the panel again and in that frame Milanković’s cyclity of insolation will be refer to just like in the past. Milanković’s theory of insolation is universal and widely developed all around the world and we except the theory and its application to be used in Europe and Chine like in America today. This is based on numerous scientific papers in last two decades in XXI century.

NOTES: “MILANKOVIĆ CYCLITY” IN MODERN ERA

1920 *Théorie mathématique des phénomènes thermiques produits par la radiation solaire*;

1941 *Kanon der erdbestrahlung und seine anwendung auf das eiszeitenproblem* (the most famous book of M. Milanković, in German);

1971-1975 CLIMAP (Climate: Long-range Investigations, Mapping and Prediction), five years project by American National Scientific Fond;

1976 Hays J.D., Imbrie J. & Shackleton N.J. *Variations in the Earth's Orbit: Pacemaker of the Ice Age*, Science, pp. 1121-1132, vol. 194;

1980 First evidence of climate change and global warming in modern period;

1982 Conference *Milankovitch and Climate: Understanding the Response to Astronomical Forcing* (Palisades, New York), (Berger, Imbrie, Hays, Kukla, Saltzman, eds.);

1988-2018 30 years of ICPP (Intergovernmental Panel on Climate Change);

2017 Three meters monument “Milutin Milanković” in Belgrade;

2020 One century of Milanković theory of insolation (anniversary year);

~2035 Melting the ice on the North Pole;

~2050 Extinction of polar bears;

~2080 End of climate change and global warming.

About Association “Milutin Milanković”

The Milutin Milanković Association is a scientific-professional association formed in 2007 with the aim of popularizing the personality and valorization of Milutin Milanković's scientific work. It gathers over 300 members, from pupils and students to academics, from the activities that Milanković was engaged in (geophysical and technical sciences), but also a large number of deputies from the humanities (artists, writers, philosophers, journalists, film workers).

Among the members there are very competent experts who permanently live and work in Serbia, but also those who live and work abroad, but regularly respond to the calls of the Association to make a significant contribution based on their rich international experience by making available educational and promotional material developed in international projects of which they were holders or participants.

The activities of the Association are realized thanks to the volunteer work of members and friends of the Association and successful cooperation with a large number of scientific and educational institutions, scientists and prominent creators in the field of science, culture and education and economy, as well as sponsors and donors. Thanks to this way of working, a large number of scientific and professional gatherings, professional and popular lectures from the activities that Milanković was engaged in (climate change, construction and timekeeping - calendar issue), a monument and other activities were erected.

Since Serbia does not have a museum dedicated to Milutin Milanković, the basic task of the Association is to collect, process and make Milanković's legacy available to the domestic and foreign public by establishing a museum exhibition.

So far, over 1,500 different documents have been collected and digitized from these sources, as well as other artifacts about Milanković's life and work (originals of old books, personal documents, paintings, drawings, photographs, diagrams, charts, professional and popular publications, video segments, newspaper articles, numerical databases and many other things).

The Association used the collected archival and museum material to organize 8 scientific and professional gatherings, publish 15 publications, and shoot 10 feature-length documentaries of various content and duration. The Digital Legacy of Milutin Milanković was established in the premises of the Association, consisting of a Documentation Center, an exhibition, a small museum display and a Virtual (digital) library, which is the embryo of the future Milutin Milanković Museum.

The work of the Association is realized in purpose-built premises of 200 square metres, which are equipped with modern furniture, necessary audio-visual and IT equipment. The premises are adapted for organizing scientific-professional gatherings and thematic exhibitions, book promotions, film screenings, holding popular lectures, as well as for receiving visits with a capacity of up to 60 visitors.



Premises of the Association Milutin Milanković



Monument Milutin Milanković in Belgrade downtown

A memorial plaque opening on 17 November 2021 - The University of Belgrade historical site of importance for the development of physics sciences



*Slavko Maksimović, President of the Association Milutin Milanković
Ivanka Popović, Rector of the University of Belgrade*