CLIMATE CHANGE OVER THE LAST 540 MILLION YEARS AND PROJECTIONS OF FUTURE CLIMATE CHANGE

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Abstract. According to the results of paleoclimatic studies, the modern stage of the Earth's climate history covers the shortest Quaternary geological period, lasting about 3 million years. The question arises about future climate changes after the currently observed warming. There is still no consensus among scientists explaining the processes currently occurring with the climate on Earth. The article analyzes climate changes since the spread of complex life forms on our planet, i.e. the presence of developed plant and animal life on Earth, which began about 542 million years ago (Phanerozoic eon). Reconstructions of the Phanerozoic temperature based on geological and isotopic data of sedimentology and paleoecology are considered. A comprehensive and quantitative assessment of how global temperatures have changed over the past 540 million years is given. To understand the trend of climate change after the end of the modern Holocene interglacial, long-term trends in changes in climatic characteristics over intervals of hundreds and tens of millions and thousands of years are considered. An overview of some of the different possible approaches to the problem of climate change is presented to demonstrate the need for an interdisciplinary view of this problem.

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1. INTRODUCTION

In the modern world, the problem of Earth's climate change on long time scales occupies a special place. Long-term data on the global mean surface temperature of the Earth are important for understanding the history of our planet and considering modern climate change. Reconstructing the Earth's climate in past geologic epochs is a challenging task.

Following the results of paleoclimatic studies of the distant past, the present stage of the Earth's climatic history covers the Quaternary geologic period, which began 2,588 million years ago. In this geologic period, starting from 800 thousand years ago to the modern era, we can distinguish glaciation cycles lasting about 100 thousand years, followed by interglacial cycles lasting 10-15 thousand years each [Jouzel et al., 2007].

Since the last 8 climatic cycles are well studied, we can roughly imagine what happened to the planet's climate during the last 800 thousand years. Thus, during the transition from the last ice age to our interglacial (Holocene), the climate changed very rapidly by geologic standards. Note that the transitions from cold to warm periods are relatively abrupt, while the transition from the interglacial to the ice age is very smooth.

Perhaps one of the reasons for the warm and long modern Holocene interglacial, following Milankovitch's theory, is related to the effect of the Earth's time-varying distance from the Sun, one of the important factors affecting climate change. The amount of solar energy received by any particular region of the globe, depending on latitude, time of day and time of year, is affected by the rotation of the globe, its tilt and the time-varying orbit of the Earth.

The end of the last glacial cycle is estimated to have occurred about 10-12 thousand years ago, but uncertainty remains about the beginning of the next glacial cycle. Warming and cooling have occurred many times in the past and should be repeated in the future.

It should be noted that the last stage of the Earth's geologic development, which brought it to its present state, falls on the Cenozoic Era, lasting from 66 million years ago to the present, in which the geologic processes that formed the continental and oceanic modern appearance took place. The Cenozoic Era was initially characterized by a warm climate. Since 65 Ma (the beginning of the Cenozoic Era), the Earth's climate has undergone a significant and complex evolution (Zachos et. al., 2001), the finer details of which are now being revealed through studies of deep-sea sediment cores. This evolution includes gradual warming and cooling trends caused by tectonic processes on time scales of 10^5 to 10^7 years, rhythmic or periodic cycles caused by orbital processes with cyclicities of 10^4 to 10^6 years, and rare rapid aberrant shifts and extreme climate transients of 10^3 to 10^5 years.

Much of our understanding of Earth's past climate comes from measuring variations in oxygen and carbon isotope concentrations in deep-sea benthic foraminifera (benthic foraminifera are single-celled microorganisms that are widely distributed in marine sediments). However, the long intervals in existing records lack the temporal resolution and age controls needed to thoroughly classify Cenozoic Era climate states and study their dynamics. Here we present a new, high-resolution, astronomically dated, continuous composition of isotopic records of benthic foraminifera, based on data from various laboratories.

Westerhold et al., 2020] present high-resolution astronomically dated data from benthic carbon and oxygen isotope measurements over the last 66 million years. The key role of polar ice volume in the predictability of Cenozoic climate dynamics is inferred from the data analysis.

The evolution of life on Earth began with the appearance of the first living creature, about 3.9

billion years ago [Futuyma, 2005]. Since about 542 million years ago (Phanerozoic eon), the time of ubiquitous and pronounced presence of advanced plant and animal life on the planet has come [Zachos et al., 2008]. Beginning with the Phanerozoic, changes in global mean temperature became relatively small to 10-15 degrees. Basically, it was a warmer epoch compared to the present time. The large climate variability in the Phanerozoic is characterized by alternating moderately warm and cold intervals of long period [Frakes, 1979].

To trace the evolution of global climate during the Cenozoic era, we focus on periodic and anomalous components of variability derived from deep-sea isotope records.

It should not be overlooked that the climate has changed more dramatically in recent times, with a faster decrease in ice extent. Understanding the causes of climate variability will allow better prediction of future climate change. The Intergovernmental Panel on Climate Change (IPCC), a UN body for assessing climate change-related science, regularly reports on climate change, e.g., [IPCC, 2023]. It should be noted that in all assessment reports the IPCC uses the same approach - anthropogenic forcing - to draw conclusions and determine the credibility of the currently observed climate warming.

There is still no consensus among scientists to explain the processes that are currently taking place with the Earth's climate. Controversial conclusions about the dominance of the greenhouse effect in the current global warming are derived from climate models. Note that climate models cannot explain the huge heat anomaly of 2023. Taking all known factors into account, the planet warmed0,2°C more last year [Schmidt, 2024] than climate scientists expected. Additional and better data are needed.

The paper [Mokhov, 2022] analyzes in detail the trends and peculiarities of the observed temperature variations. It is noted that the regime of the modern climatic system of the Earth is comparable to the regime of the Holocene optimum. At the same time, the increase in global surface temperature is accompanied by a rapid increase in the number of natural disasters, primarily due to hydrological and meteorological anomalies. Thus, successful forecasting of future climate changes requires information on the state of the environment over long time intervals.

The question of future climate change after the end of the observed climate warming arises. Analyses of different proxy data, such as unicellular organisms: foraminifera in marine and ocean sediments covering different time intervals, can help to clarify the debate on the causes of the current global warming and gain a better understanding of the future climate change trend.

This paper presents Phanerozoic temperature reconstructions based on geologic and isotopic data from sedimentology and paleoecology. Lithologic climate indicators such as coals, bauxites, tillites, and evaporites are used to reconstruct climate zones, and geochemical indicators are used to determine paleotemperature from oxygen isotope content.

2. FACTORS ASSOCIATED WITH CLIMATE CHANGE OVER TIME AND THEIR TRENDS

In order to understand the trend of climate change after the end of the modern interglacial, the long-term trends in climate characteristics at intervals of hundreds and tens of millions of years in different regions of Antarctica were considered in [Dergachev, 2023]. The analyzed data on climate change after the end of the last ice age and present-day climate changes indicate a slowing down of the warming process in the Antarctic region, but their further trends remain unclear. Dergachev [Dergachev, 2024] analyzes climate change data and traces the relationship between changes in global mean surface temperature and climatic factors over the past 540 million years.

The study shows that there is a close correspondence between the reconstructed Phanerozoic records of cosmic ray flux and temperature. Royer et al. (2004) reviewed the geologic records of CO_2 and glaciations and found that CO_2 was low during periods of prolonged and widespread continental glaciations and high during warmer periods. It should be noted that Royer et al. (2004) demonstrated a closer correspondence between the reconstructed Phanerozoic cosmic ray flux and temperature records than between CO_2 and temperature (Fig. 2). According to the data in the above figure, cooling occurred at higher cosmic ray intensities. The correspondence between atmospheric CO_2 concentrations and globally averaged surface temperatures during the Phanerozoic (last 542 Ma) is traced in Royer et al. (2006). To assess the strength of the relationship between temperature and CO_2 concentration, 490 published CO_2concentration data were compared with records of global cooling. It was found that geologic records of CO_2 concentrations showed low values during periods of prolonged and widespread continental glaciations and high values during warmer periods. To quantitatively test the importance of potential climate forcing, data on sea surface temperature changes in the Phanerozoic, inferred from $\delta^{18}O$ concentrations of shallow marine carbonate, were used. It should be noted that the above work demonstrates a closer correspondence between the reconstructed Phanerozoic cosmic ray flux and temperature records than between CO_2 and temperature (Fig. 2). Thus, periodic fluctuations in the cosmic ray flux in time can influence climate change.

Estimates of global mean surface air temperature over the ~540 Ma Phanerozoic eon in Figure Figure 2A are derived from measurements of stable oxygen isotopes in fossil shells [Shaviv, 2003]. On long time scales it is also possible to trace the influence on climate of cosmic rays, the F flux of which was reconstructed in [Shaviv, 2002; Shaviv, 2003] using iron meteorite impact ages.

The relationship between temperature changes (ΔT) and cosmic ray flux F and during the Phanerozoic was investigated in [Shaviv, 2005]. Figure 3 shows the response of climate to changes in cosmic ray flux and radiation balance. The upper curves describe the tropical temperature (ΔT) anomalies and the reconstructed F flux using iron meteorite impact ages [Shaviv, 2003]. The results demonstrate a close correspondence between the reconstructed Phanerozoic records and the cosmic ray flux. As noted above, cooling occurred at higher cosmic ray intensities. The blue line ***1*** depicts the nominal flux F, while the yellow shading delineates the allowable error range. The dotted curves represent additional reconstructions of F that fit within the acceptable range (together with the blue line, these three curves denote the three reconstructions of F used in the model simulations). The red curve ***2*** describes the nominal F reconstruction after its period has been fine-tuned to best fit the low-latitude temperature anomaly (i.e., it is the "blue" reconstruction after the exact periodicity of F has been fine-tuned within the F reconstruction error). The shaded areas at the top of the figure reflect periods of cooling.

3. PHANEROZOIC TEMPERATURE RECONSTRUCTIONS, BASED ON GEOLOGIC AND ISOTOPIC DATA FROM SEDIMENTOLOGY AND PALEOECOLOGY

The pattern of global mean temperature change during the Phanerozoic can be traced from data obtained in (Frakes, 1979; Scotese and Wright, 2018; Frakes et al., 1992) and others. Overall, these studies allow us to trace and understand the interconnectedness of the various natural processes affecting the formation of the Earth and to make better predictions about past and future temperatures.

Figure 4 presents temperature reconstructions associated with the most significant impacts of natural processes on climate. The lack of coupling between different fields of knowledge is discussed, concluding with the need for coupling between different fields of knowledge as a solution to find measures to address the problem and, above all, to understand climate change globally and comprehensively.

One of the first reconstructions of paleotemperatures over the Phanerozoic interval (Figure 4A), assuming alternating glacial periods and comparatively warmer periods derived from geologic data, is presented in [Frakes, 1979]. The global mean temperature reconstruction **(1)** is presented in [Scotese and Wright, 2018], and reconstruction **(2)** is discussed in [Frakes, 1979; Frakes et al., 1992]. Calcite ∂^{18}O levels in tropical marine shallow waters **(3)** are represented by the red curve in the figure [Shaviv et al., 2023].

In Figure 4B, temperature reconstructions associated with the most significant impacts of natural processes on climate are presented from measurements of oxygen ^{18}O isotope ratios. The global temperature model discussed in this paper includes estimates of global mean temperate temperatures, varying tropical temperatures, deep ocean temperatures, and polar temperatures, providing a deeper understanding of the interconnected geologic, tectonic, paleoclimatic, paleoceanographic, and evolutionary events that influenced Earth's past temperature. The lack of connectivity between different fields of knowledge is discussed, concluding with the need for interconnectivity between different fields of knowledge as a solution to find measures to address the problem, and above all, for a global and integrated understanding of climate change.

The results of [Scotese et al., 2021] and [Shaviv et al., 2023] provide a comprehensive and quantitative assessment of how global temperatures have changed over the past 540 million years (Figure 4C). Scotese et al., 2021] consider two main groups of climate drivers for the Phanerozoic: 1) external drivers, which depend on the Earth's interaction with its celestial environment; and 2) internal drivers of the Earth system, whose changes arise from various geologic processes. The best-known external driver is the Milankovitch cycles, in which gravitational forces acting on the Sun, Moon, and planets affect the parameters of the Earth's orbit. Another external driver appears to be variations in the flux of cosmic rays, which have a large impact on climate. Cosmic rays are a stream of high-energy particles with stable charges. The composition of cosmic rays is dominated by protons, but there are also electrons, helium nuclei and heavier chemical elements. Cosmic rays come to the Earth from all directions from outer space and constantly bombard its atmosphere. They come from a variety of sources in space, including the Sun and the remnants of supernovae. Cosmic rays are a unique phenomenon in space, and the study of their properties and origin is important for understanding cosmic physics and the evolution of the universe. Cosmic rays can induce various physical processes in the Earth's atmosphere.

The history of global temperature changes during the Phanerozoic has been summarized in a "paleotemperature time scale" that subdivides many past climate events into 8 major climate regimes; each standing for 3-4 pairs of warming and cooling episodes. It describes how these past temperature events have been affected by geologic processes such as eruption of large magmatic provinces (warming) and bolide impacts (cooling).

The paleotemperature model presented in this paper allows for a deeper understanding of the interrelated geologic, tectonic, paleoclimatic, paleoceanographic, and evolutionary events that influenced the past temperature of the Earth. It should be noted that from the analysis of the results obtained and presented in the figures, we cannot draw an unambiguous conclusion about the sharp onset of cooling after the end of the modern interglacial period, although the global temperature trend indicates a decrease in temperature. At present, we are apparently passing through a phase of maximum warming.

Recently, the authors [Judd et al., 2024] wanted to obtain a reliable timescale on the Phanerozoic time scale. An improved reconstruction of the paleotemperature timescale over 485 million years includes glaciations, hot climate periods, plate tectonic movement, biological proxies of extinct species, interpolation of disparate data in space and time, etc., covers the Earth's surface temperature history over the last 485 million years. By combining the models with geologic indicators, they constructed a new Phanerozoic temperature curve (Figure 5). The figure shows the global average temperature. The gray gradient indicates different confidence level, the black curve is the average value. The results are in good agreement with the previously established periods of glaciation and warming. As the results of the study indicate, temperatures over the past 485 million years have varied much more than previously predicted.

During this geologic time span, the entire diversity of life arose on Earth, the land was populated, and several mass extinctions occurred. In addition, new work has confirmed a strong correlation between atmospheric carbon dioxide and temperature. This work also shows that the modern average temperature of 15 degrees is much lower than what prevailed throughout most of the Phanerozoic.

4. CONCLUSIONS

In summary, the study of paleotemperature changes over time, reveals important insights into the history of the Earth system and the fundamental causes of climate change on geologic time scales. This can help to better understand the challenges of future global climate change.

The interdisciplinary approach is the approach that can make the most comprehensive contribution to presenting global solutions, with contributions from all fields of knowledge framed within the scientific method.

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CONFLICT OF INTERESTS

The author declares that he/she has no conflict of interest.

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FIGURE CAPTIONS

Fig. 1. Global mean temperature in the Phanerozoic and climate drivers over a 540 Ma interval: *1*, combined geochemical/lithological temperature reconstruction (solid line) [Shaviv et al., 2023]; *2*, reconstruction [Scotese, 2021] (dashed line); *3,* modeled temperature (dashed green line). Additional plots represent different components of the model: *4* - solar luminosity increase (dashed line, purple); *5* - CO_2 (dashed double dotted line); *6* - atmospheric ionization (dashed line), shaded areas are 1σ and 95% confidence error regions based on geological data and isotopic studies.

Fig. 2. Changes in temperature and cosmic ray flux over the Phanerozoic time interval: A) Blue curve *1)* corresponds to calculated temperature deviations relative to the present [Veizer et. al., 2000]; curves *2*) and *3*) are corrected for changes in seawater Ca++ concentration [Horita et al., 2002] and CO_2based on either GEOCARB III or a proxy. B) Cosmic ray flux (relative to the present). C) Intervals of cooling (shaded regions) and warming.

Fig. 3. A - Changes in cosmic ray flux F and B - temperature T (geologic reconstruction) [Shaviv, 2005]. *A* - Cosmic ray flux F (relative to the present) as reconstructed [Shaviv, 2002]. B - Temperature change. The black curve (geologic reconstruction) corresponds to temperature deviations relative to the present, while the red curve (temperature reconstruction from oxygen isotope data in calcite and aragonite shells calculated [Shaviv and Veizer, 2003] from the "10/50" $\delta^{(18)\ O}$compilation presented in [Veizer et al, 2000]), and the red curve describes the nominal reconstruction after its period was fine-tuned within the measurement error to best match the low-latitude temperature anomaly. The glacial and cool climate intervals are highlighted at the top of the figure, as in Figure 2B.

Fig. 4. *A* - Phanerozoic global mean temperature reconstructions: (1) based on geologic data and isotopic studies, black curve [Scotese and Wright, 2018]; (2) based on sedimentology and paleoecology, green curve [Frakes, 1979; Frakes et al., 1992]. Calcite $\partial^{18}O$ levels in tropical marine shallow waters (3) - red curve [Shaviv et al., 2023].

B - Long-term evolution of mean Earth surface temperature from measurements of oxygen ^{18}O isotope ratios [Veizer and Hoeffs, 1976] on the time scale of the Phanerozoic [Veizer et al., 1989]. The results of measurements of the Earth's average surface temperature for the last 500 Ma and the most significant impacts associated with climate change in this time interval are discussed in [Nunes and Ferreira, 2022].

C - Comparison of temperature reconstructions: 1 - combined reconstruction (solid line) based on lithologic and geochemical data for long-term scales and oxygen isotope data for mid-temporal scales (10-20 Ma) [Shaviv et al., 2023]; 2 - temperature reconstruction [Scotese et al., 2021] (dashed line).

Fig. 5. Relationship between reconstructed temperature T and CO_2concentration in the Earth's atmosphere during the Phanerozoic. The CO_2 reconstruction is based on data from [Foster et al., 2017].

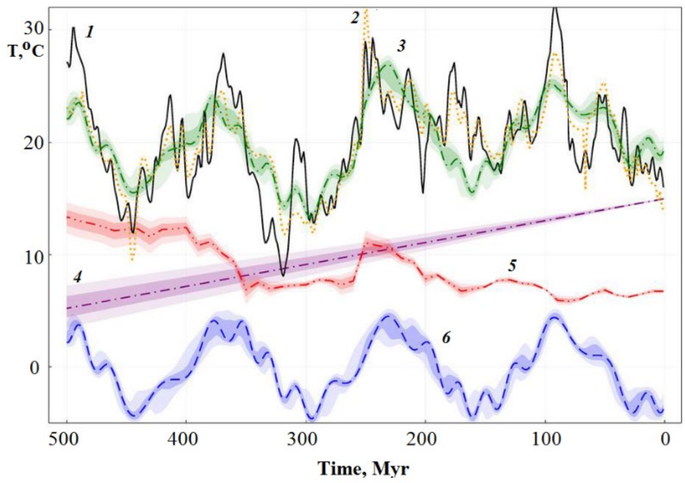

T,⁰C
30
20
10
0
1
2
3
4
5
6
500
400
300
200
100
0
Time, Myr

Fig. 1.

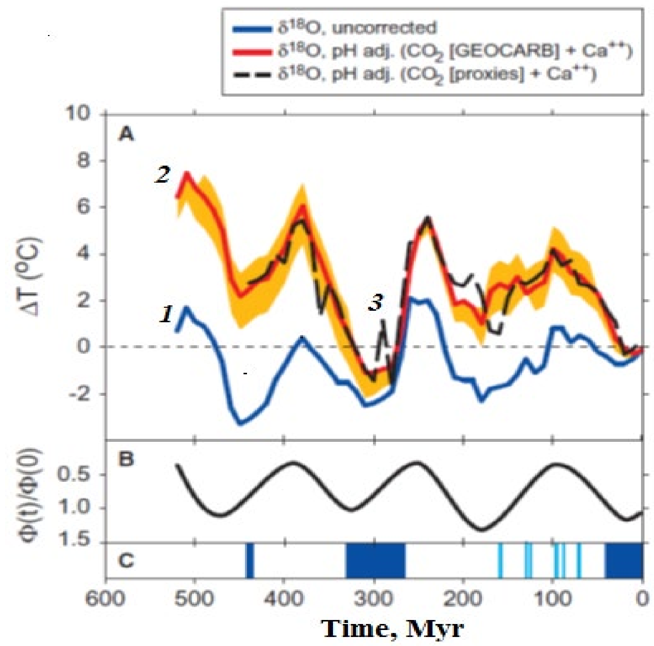
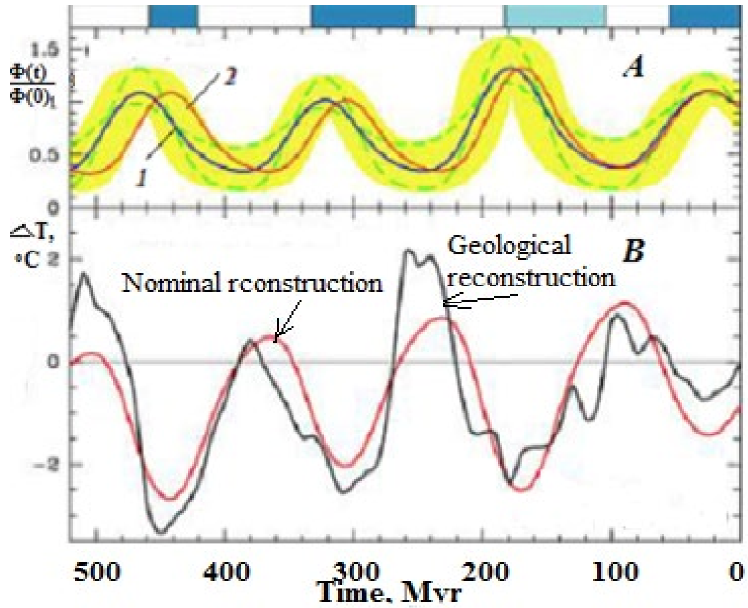

δ18O, uncorrected
δ18O, pH adj. (CO2 [GEOCARB] + Ca++)
δ18O, pH adj. (CO2 [proxies] + Ca++)
A
B
C
ΔT (⁰C)
Φ(t)/Φ(0)
1
2
3
Time, Myr

Fig. 2.



A
B
1
2
1.5
1
0.5
0
$\frac{\Phi(t)}{\Phi(0)}$
ΔT, °C
2
0
−2
Nominal rconstruction
Geological reconstruction
500
400
300
200
100
0
Time, Myr

Fig. 3.

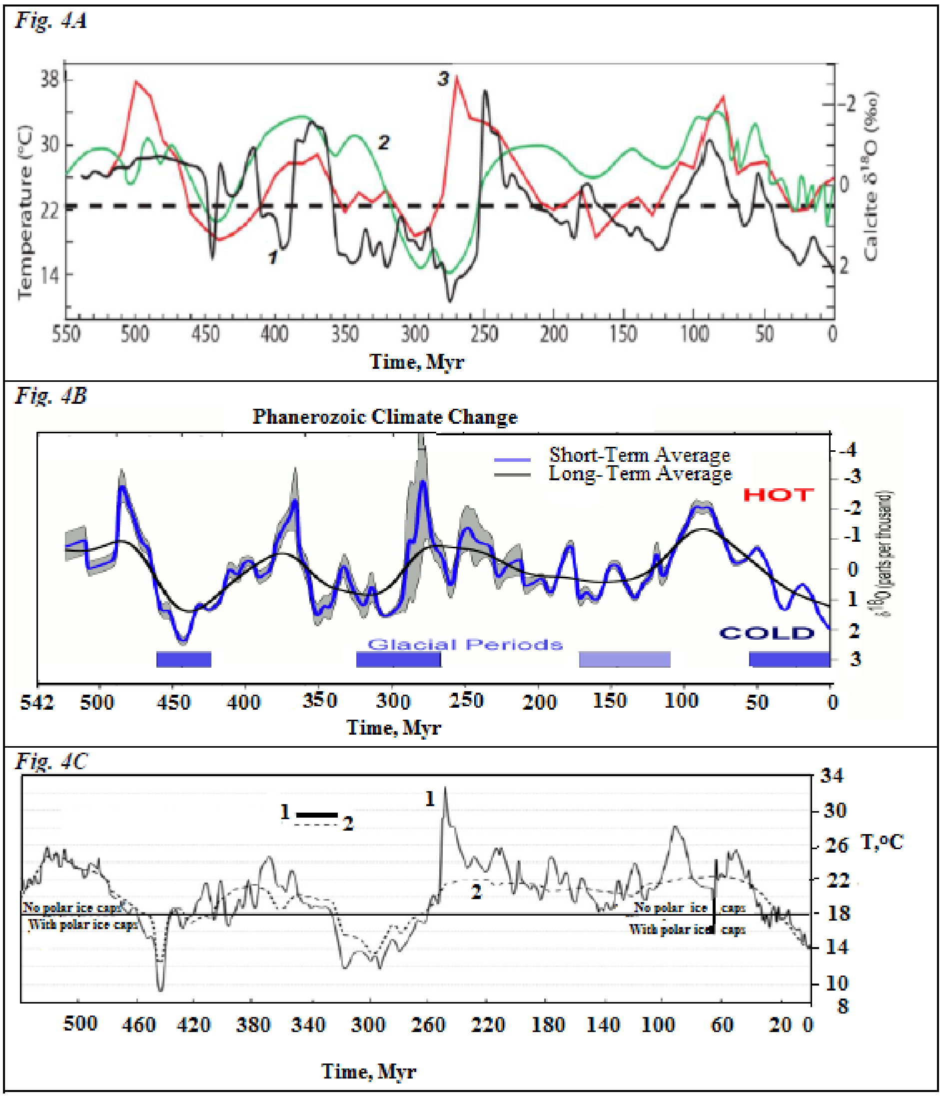
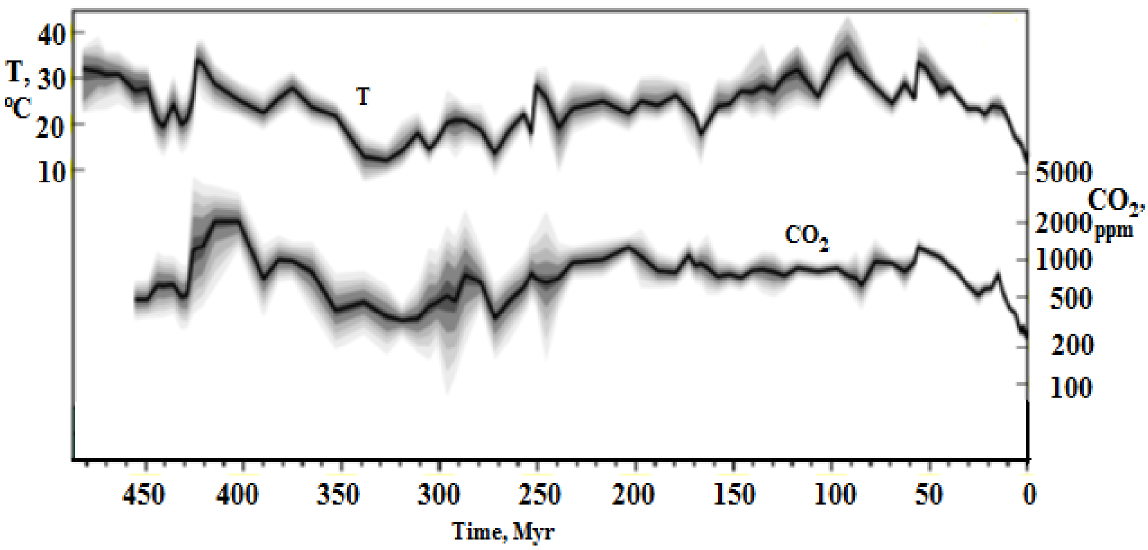


Fig. 4A
Temperature (°C)
Calcite δ18O (‰)
Time, Myr
Fig. 4B
Phanerozoic Climate Change
Short-Term Average
Long- Term Average
HOT
COLD
Glacial Periods
Time, Myr
Fig. 4C
T,°C
No polar ice caps
With polar ice caps
Time, Myr

Fig. 4.



T, °C
T
CO2
CO2, ppm
Time, Myr

Fig. 5.