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The role of oxygen in the functioning of the Earth system: past, present and future

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Abstract

In the Solar System, the coming into existence of a peculiar, fully developed atmosphere on Earth was determined by the 'Great Oxidation Event' at the turn of the Proterozoic and Palaeozoic. Within about 600 million years, there were large changes in oxygen concentrations in this atmosphere, ranging from 15 to 35 per cent, having been determined by a combination of cosmic-climatic, tectonic-volcanic and biological phenomena. A particular environmental change occurred at the beginning of the 19th century, as a result of the overlap of the end of the natural Little Ice Age and the beginning of anthropogenic warming of the 'industrial revolution'. According to the author, the rate of human impact on environmental changes is estimated at about 15 per cent. The appearance of mankind brought new changes in the natural environment, including the oxygen content of the air. The current scale of anthropogenic impact justifies the introduction of a new time slice in the planet's history - the Anthropocene. The functioning of civilisation is conditioned by meeting energy needs, to be implemented by creating a system of energy generators, among which the heat of the Earth should be an important component. The energy generated from this inexhaustible and cost-free geo-resource should be seen as the most ecological among all currently used energy carriers.

Keywords: Environment, oxygen concentration changes, Anthropocene

1. Introduction

The issue of the genesis of the Earth's oxygen atmosphere and its variability after the Great Oxidation Event is as important as are problems of carbon dioxide, methane or ongoing global warming. For human life to be possible, the oxygen content in atmospheric air cannot be lower than 15 per cent. Such a value has been maintained for the last 600 million years, but has been subject to significant, naturally conditioned fluctuations, reaching even >35 per cent. In Earth history, two significant increases in oxygen concentration (early and middle Palaeozoic and Mesozoic, respectively), as well as two phases of a decrease of this gas (i.e., late Palaeozoic and from the Paleogene-Neogene turn onwards) are recognised. These fluctuations were determined by a combination of external (cosmic and climatic) and internal (tectonic and volcanic) factors, as well as biogenic factors. Initially, and for a very long time afterwards, these were natural; only recently can they be ascribed to human impact (for details see: https://earthhow.com/atmosphere-history/ and https://ncas.ac.uk/our-science/long-term-global-change/).

The present review uses available data on oxygen content in the air and presents these mainly within a palaeoenvironmental context. In addition, on the basis of these data, the author justifies the introduction of a new stratigraphical term – Anthropocene. He also discusses the rational use of oxygen and the provision of our energy needs by generators of low oxygen consumption.

2. Natural conditions of atmospheric oxygen concentration

Unique in the Solar System, the fully developed oxygen atmosphere of the Earth has existed for about 600 million years, or just over 13 per cent of the history of the globe. The oxygen atmosphere will persist for a very long time, possibly for another billion years. It is likely that, due to the continuous increase in temperature of the Sun, the functioning of photosynthesis will be disturbed, resulting in a rapid disappearance of oxygen, with an increase in methane content. Oxygen-requiring organisms will perish., as indicated by modelling of climatic, biological and geological systems carried out by NASA experts, such as Kazumi Ozaki (Tokyo Institute of Technology, Japan) and Chris Reinhard (Georgia Institute of Technology, Atlanta, USA) (Reinhard et al., 2017). However, currently observed trends in the reduction of oxygen content in the atmosphere indicate that concentrations critical to human life will occur in about 10,000 years. In scientific literature, there is also an alternative view about a more rapid natural decay of oxygen, which will be addressed in the final part of the present paper. In the long history of our planet, significant changes in its gaseous envelope have taken place (Cating & Claire, 2005). Three main stages of the composition of the Earth's atmosphere have been recognised (Fig. 1).

The primaeval atmosphere was mostly hydrogen, probably with the addition of water vapour, methane and ammonia (Zahnle et al., 2010) and similar to the present composition of the atmospheres of Jupiter and Saturn. During hundreds of millions of years of cooling of the embryonic Earth, anaerobic single-celled organisms without a nucleus, the so-called archaea, and primordial bacteria appeared.

Significant changes in the Earth's atmosphere occurred about 4 billion years ago, as a result of volcanic activity and the so-called 'late heavy bombardment' (LHB), between 4.1 and 3.8 billion years ago (Bottke & Norman, 2017). From 4 to 3 billion years ago, an atmosphere with dominant nitrogen and a significant content of carbon dioxide formed. Carbon dioxide largely dissolved in seawater, where it reacted with calcium and magnesium, derived from weathering of igneous rocks. This is how the first carbonate rocks were formed, the oldest of which are estimated to be 3.8 billion years old.

Very early in the history of the Earth, there were distinct and prolonged periods of cooling, including extensive glaciations. In an extreme case, there was even glacio-nivation of the entire globe – the so-called 'Snowball Earth'. The oldest, although not fully documented, long-lasting glacial period is indicated by the so-called Pongola Phase (~2.9–2.8 billion years ago). On the other hand, geologically well-confirmed phases of Earth's glaciation have

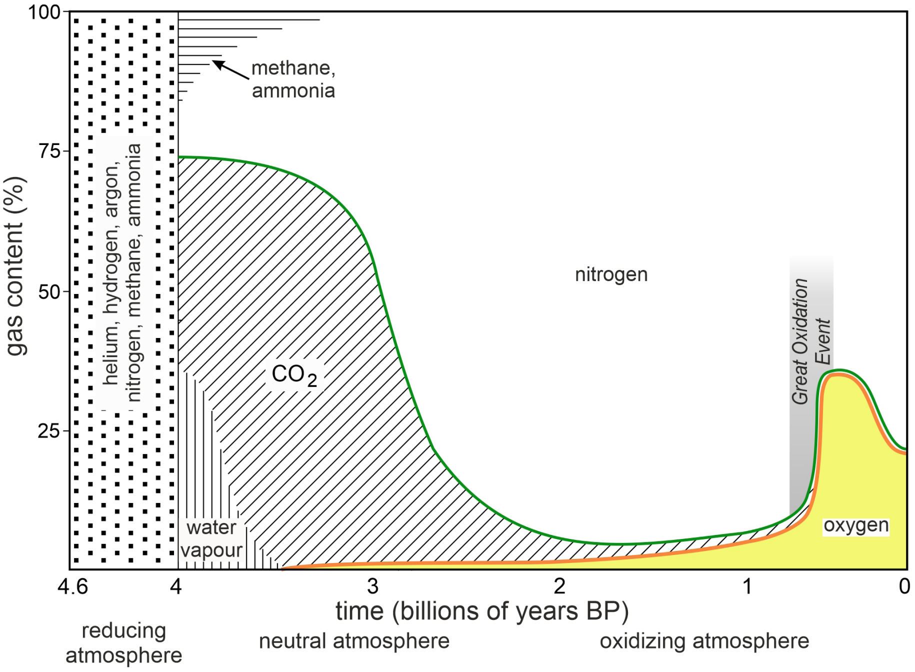

Fig. 1. Changes in the Earth's atmosphere (modified from Chwieduk, 2011); the present author places the boundary between a neutral and oxidising atmosphere differently, i.e., not at ~2 billion years ago, but rather at ~600 million years ago, during the Great Oxidation Event (see Fig. 2).

existed since the late Proterozoic (Timeline of glaciation, 2022), inclusive of the Huronian Glaciation between ~2.4 and 2.1 billion years ago. It should be noted that this event took place in an atmosphere with a negligible amount of oxygen – 'an oxygen-free atmosphere'. However, the following long-term cold phases functioned in an oxygen-containing atmosphere: Sturtian-Marinoan-Gaskiers-Baykonur (~0.7–0.5 billion years ago), the Karoo (~0.4–0.3 billion years ago) and, finally, the late Cenozoic Ice Age (from about 0.04 billion years). These long-lasting, alternating cold and warm epochs are referred to by the author as megaglacials and megainterglacials (Stankowski, 1996). During the late Cenozoic Megaglacial, there were thermal fluctuations – the basic taxa of thermal changes of the globe – glacials and interglacials. These, in turn, are divided into shorter periods of climate change (stadials/interstadials, phases/interphases, oscillations, etc.). The complex cyclicity of climatic and geomorphological changes during the Pleistocene was presented by Kozarski (1986). It should be emphasised that this rhythmicity consisted not only in changes in temperature, but also in atmospheric composition, which will be discussed in more detail below.

The first life forms are dated at ~3.5 billion years (Schopf, 1983; Chwieduk, 2011). The emergence of single-celled organisms led to the initiation of oxygen in the atmosphere. Its clear increase was due to multicellular organisms. The most important role was played by photosynthetic cyanobacteria, as documented geologically by stromatolites. The oldest are dated to about 3.4 billion years. During a long time (approximately 1.9–1.0 billion years) of slow oxygen buildup, it reacted with iron oxides, sulphides and carbonates to generate marine iron deposits with interbeds of silica-rich rocks.

Starting from about 2.15–2.08 billion years ago, a clear process of increasing the oxygen content in the Earth's atmosphere began. Very early, the so-called 'Great Oxidation Event' (increase in oxygen concentration to about 15 per cent) may have occurred, at around 2.5 billion years ago (Martin et al., 2017) (Fig. 2). However, this hypothesis is not widely accepted in the literature. Most likely, the concentration of oxygen in the air remained low for a long time, at least until about 1 billion years ago (Lyons et al., 2014). Most studies indicate that the significant increase in oxygen content occurred later, from about 1 billion years ago, or even less than that. The onset of the 'Great Oxidation Event' should therefore be dated to the turn of the Proterozoic and Palaeozoic, or about 650–600 million years ago. The concentration of oxygen in the atmosphere reached its maximum (approximately 35 per cent) around 300 million years ago. Since then, there have been major fluctuations in oxygen content in the atmosphere (Fig. 3).

It is impossible to indicate clearly any specific factor or several basic factors that caused significant changes in oxygen content in the atmosphere during the Phanerozoic. Long-term trends in thermal and electromagnetic changes of the Earth System seem to be very important. It is therefore necessary to pay attention to the interaction of many natural factors of astronomical-climatic, tectonic-volcanic and biogenic origin. The last-named appear to be particularly important.

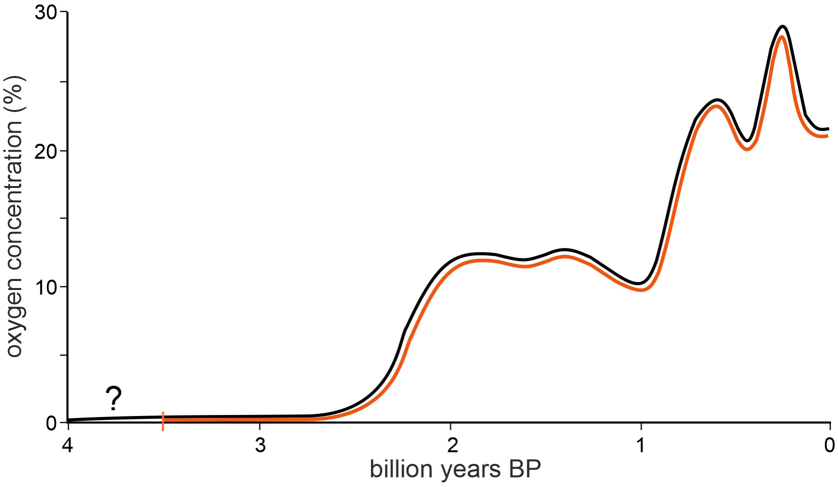

Fig. 2. The probable course of changes in oxygen concentrations in Earth's atmosphere during 4 billion years (according to Martin et al., 2017). Surprisingly, the oxygen curve in the air does not start around 3.5 billion years ago, as the author's modification of the graph shows (in red). The oxidation of the atmosphere took place in two stages; the first phase ofrapid increase in oxygen content was supposed to have occurred between 2.5 and 2 billion years ago (similar interpretation by Waters et al., 2022), while the second phase occurred <1 billion years ago.

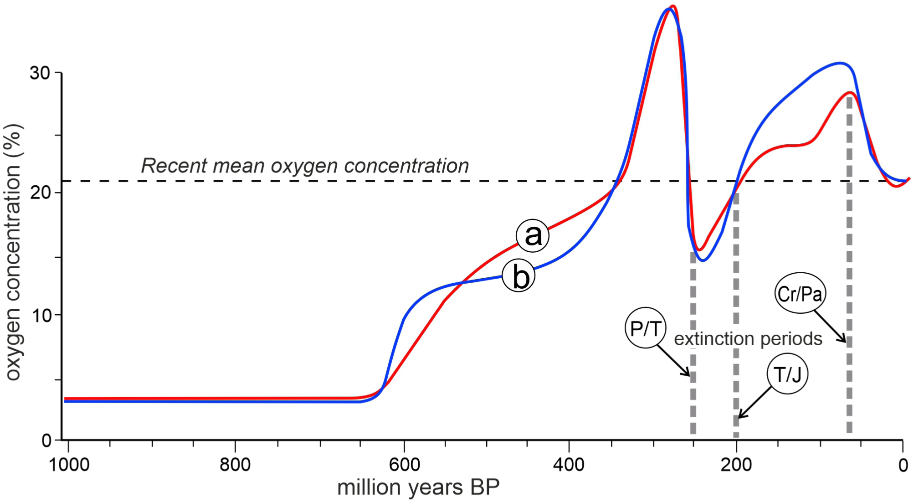

Fig. 3. Oxygen content in the Earth's atmosphere during the last billion years, with reference to the current concentration of ~21 per cent. Graph *a* is by Entwicklung der Erdatmosphäre -Wikipedia 2022 and Colealeman.de/unterricht 11_htm_files/Uratmosphaere und Entstehung des Lebens.pdf, while Chart *b* is by Graph (2018). Periods of great extinctions: P/T – Permian/Triassic, T/J – Triassic/Jurassic, Cr/Pa – Cretaceous/Paleogene.

Fluctuations of the composition of the atmosphere were conditioned differently. The occurrence of the 'Great Oxidation Event' was supposedly caused by cynobacteria (compare Aiyer, 2022). However, changes in the composition of the air during the oxygen atmosphere were caused by a combination of extraterrestrial and terrestial phenomena. Synthetically, they were:

- cosmogenic energy streams and impacts of large-scale extraterrestrial matter;
- global tectonics (with changes in the position of lands and seas, affecting the distribution of thermal energy), orogenic-tectonic-volcanic activity, biogenetic impulses (Schmidt-Rohr, 2020).

A variety of factors with different environmental impact resulted in intensification or reduction of the distinctiveness of changes in atmospheric composition.

After the explosion of life ('biological big bang'), at the turn of the Proterozoic and Palaeozoic, there was a steady increase in oxygen content of the atmosphere. The formation of the super-continent Pangaea (Fig. 4) contributed to the intensive development of organisms under favourable climatic conditions, including vegetation that led to the formation of coal. A good example of the geodiversity of coal-bearing environments of that time is the territory of Poland. These deposits formed under var-

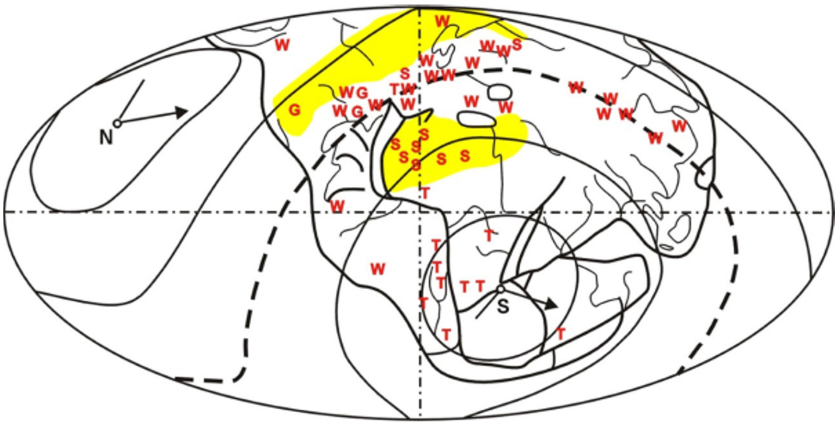

Fig. 4. Pangaea super-continent at the end of the Palaeozoic, covering all climatic zones; interpretations by A. Wegener and W. Köppen from the early 20th century were used. Coal (W) formed in the equatorial zone, while in tropical zones (highlighted in yellow) salt and gypsum were deposited (S). Vast areas around the south pole (arrows at both poles illustrate the direction of their movement) were glaciated and tillites (T) formed there. During the long Carboniferous–Permian period there were climate fluctuations, which are documented geologically by coal layers, evaporite cyclothemes and glacial-fluvioglacial deposits.

ious morphogenetic conditions: in mid-mountain basins (Sudety Mts), in vast deltaic plains (Upper Silesia) and in shallow sea bays (Lublin Upland).

As a result of these astronomical, climatic and geoenvironmental phenomena, there was an increase of oxygen in the Earth's atmosphere, reaching the aforementioned concentration of about 35 per cent. This increasing trend in oxygen concentration was halted as a result of a range of phenomena, but mainly Hercynian (Variscan) orogeny with strong tectonic and volcanic impulses. The intensity of volcanic processes is evidenced by the so-called Siberian traps (extensive and thick lava covers formed as a result of fissure eruptions) dated to the turn of the Palaeozoic and Mesozoic. The formation of giant volcanic covers must have strongly influenced the Earth's atmosphere.

At the end of the Palaeozoic occurred also significant climatic fluctuations (cooling of atmosphere and oceans), which resulted in extensive Carboniferous-Permian glaciations ('Karoo Megaglacial').

Large impacts leading to the formation of extensive craters are dated similarly: for example, in Antarctica (approximately 500 km in diameter), as well as in the land-ocean zone of Australia (approximately 150 km in diameter).

The process of the breakup of Pangaea became a later addition to significant disturbances in the Earth's geosystem (Fig. 5).

All the factors mentioned here negatively affected the functioning of biosystems. This resulted in the largest extinction in the history of the Earth: more than 90 per cent of marine organisms and in excess of 70 per cent of terrestrial organisms probably went extinct (Song et al., 2013). The composition of the biocoenosis typical of the Palaeozoic, practically ceased to exist and was not to be rebuilt. This applies to many groups of organisms, for example trilobites, goniatitid ammonites and rugose corals.

Geoenvironmental transformations of the globe led to a significant decrease in the oxygen content of the atmosphere, from about 35 per cent 250 million years ago to approximately only 15 per cent.

In the Mesozoic and early Cenozoic, which may be referred to as the 'Mesozoic Megainterglacial', another cycle of intense oxidation took place. Under conditions of a warm period in the history of the Earth, marine carbonate sedimentation dominated, and later (in the Cretaceous, Paleogene and Neogene) it was continental lignite sedimentation. Climate fluctuations occurring at that time also led to the formation of amber from tree resin. Conditions favourable to the luxuriant development of the biosphere caused an increase in the oxygen content in the atmosphere. Around 170–100 million years ago, the oxygen concentration was at 23–24 per cent, then increased and around 70 million years ago, it reached about 27–28 per cent, and perhaps even slightly over 30 per cent.

At the turn of the Mesozoic and Cenozoic, the subsequent change in the trend of oxygen content in the atmosphere began. Similar to the oxygen-reduction period at the turn of the Palaeozoic and Mesozoic, this was the result of the interplay of many factors. Alterations in the distribution of land (including their orography) and oceans caused serious changes in the circulation of sea currents and winds. This resulted in a change in the distribution of heat around the globe. There was a trend of lowering the temperature of ocean waters, as documented by stable oxygen isotope data from the tests of planktic and benthic foraminifera (van Andel, 1994). The Mesozoic–Cenozoic boundary is linked to the impact of a bolide; this formed the Chicxculub crater with a diameter of about 180 km

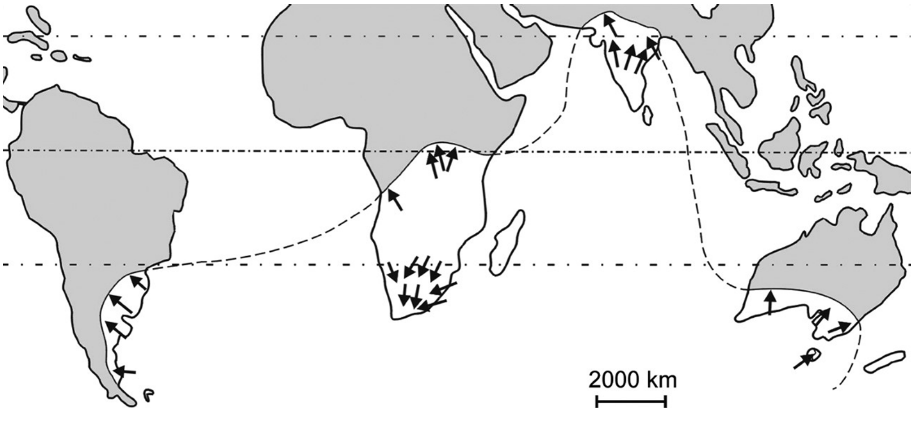

Fig. 5. The effect of the breakup of Pangaea around the south pole. The sketch shows the modern distribution of continents with the extent of tillites from Carboniferous–Permian glaciations (white colour). The arrows denote the directions of ice sheet movement (according to Stankowski, 1977, 2019).

in the land-sea area of northeast Yucatán (Mexico). It was probably the largest, but not the only, impact of that time. Besides, cosmic dust enveloped the entire Earth. Geologically, this is documented by the so-called 'dark layer' of limited thickness, enriched in iridium, which is rare in the Earth's crust.

At the turn of the Mesozoic and Cenozoic, another mass extinction occurred. Three quarters of plant and animal species died out; dinosaurs almost completely disappeared, as well as ammonites and belemnites. As with the Permian crisis, the Cretaceous extinction became an important biological turning point. Mesozoic organisms did not recover in the Cenozoic, and mammals became dominant.

In the Late Cretaceous orogenic movements (Laramide Phase) occurred. In India, the 'Deccan Traps' formed, which must have had a strong influence on the composition of the atmosphere. The tectonically controlled process of atmospheric oxygen depletion was intensified during the Neogene (Miocene) phase of Alpine orogeny. An important role was played by volcanic processes occurring in several phases of varying intensity in all areas of the Alpine tectonics, from the Late Cretaceous to the turn of the Pliocene and Pleistocene. A good illustration of long-term and intense tectonic processes is the Peruvian part of the Andes (Paulo, 2008; Paulo & Gałaś, 2011). The tectonic movements of the Mesozoic/Cenozoic turn and the Neogene were connected with changes in the location of lands and seas, which determined changes in heat distribution. The global circulation of low latitudes, which allowed high temperatures to be maintained around the globe, was eliminated. Instead, a cold polar circulation developed, which isolated Antarctica (van Andel, 1994).

The Cenozoic trend of lowering global temperatures (Earle, 2019) led to the Cenozoic Megaglacial, which continues to the present day. Geoenvironmental differences of the northern and southern hemispheres determined the quite variable duration of glaciations in both hemispheres (Earle, 2019; van Andel, 1994; Stankowski, 1996) (Fig. 6). In the high latitudes of the southern hemisphere, glaciers existed for almost 50 million years (Birkenmajer, 1990, 1992), while the onset of glacial history in the northern hemisphere may be dated to about 10 million years ago, but certainly to the last 3 million years (Imbrie & Imbrie, 1979; Mojski, 1993).

The general trend of cooling of the Earth's surface finds credible documentation for the last 5 million years, a period characterised by climatic cyclicity repeated every approximately 100,000 years. This cycle is marked by successive glacials and interglacials during the last 500,000 years (Fig. 7). These fluctuations were conditioned by the variability of the eccentricity of the Earth's orbit and changes in solar radiation. The latter were recognised by Milankovič (1914), who presented them in the form of curves for different latitudes of the northern hemisphere. They were reinterpreted by B. Eberl, who distinguished sixteen cold climatic phases in the Alps (Imbrie & Imbrie, 1979). The presence of such a large number of cold oscillations

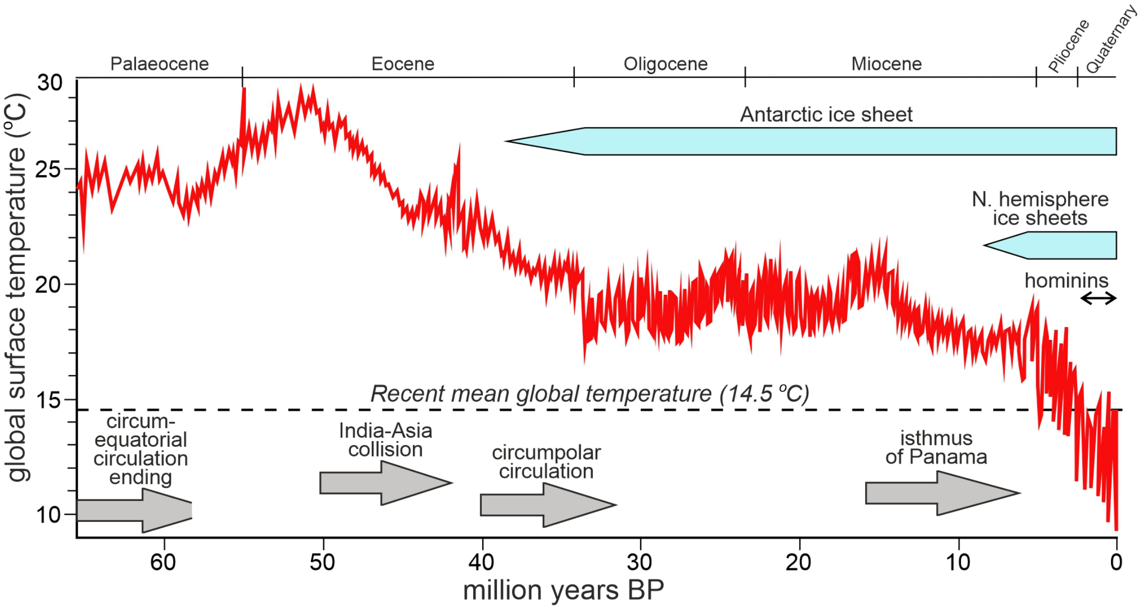

Fig. 6. Trends of temperature changes during the last 65 million years and selected geoenvironmental events of significant importance for global thermal conditions. Note the different glaciation time spans of the northern and southern hemispheres (modified after Earle, 2019).

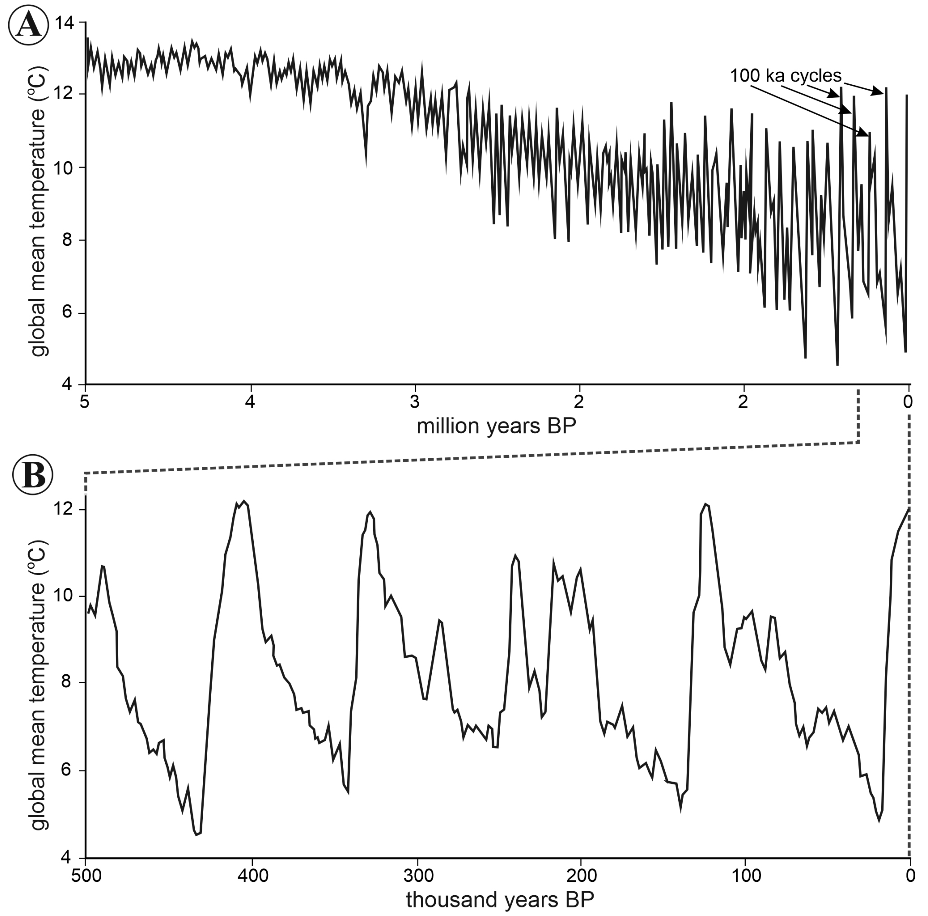

Fig. 7. Global temperature changes. **A –** Data from oxygen isotope analyses from marine deposits over the last 5 million years; **B –** Rhythm of temperature changes over the last 500,000 years (modified from Earle, 2019).

in the Alpine area indicates an overlap of secondary rhythms with shorter intervals over a period of approximately 100,000 years.

Isotope data from cores of oceanic sediments also confirm the existence of multi-period temperature cyclicity in the past. The rhythmicity of the so-called isotope stages, developed by Shackleton & Opdyke (1973), is a good illustration of this. It should be added that these studies refer to an environment that was less susceptible to temperature changes than on land.

A spectacular example of different rhythms of temperature changes is the period of the last 150,000 years (Fig. 8). Results of an analysis of air bubbles from glacier ice of Antarctica and Greenland show not only a rhythm of 100,000 years, but also a shorter repetition. Similar trends in changes in carbon dioxide and methane content were identified in the Vostok ice core in Antarctica (Dawson, 1992). These studies indicate indirectly the existence of fluctuations in the oxygen content in the Earth's atmosphere. Unfortunately, the amplitude of these changes has not been determined.

During the last 20,000 years, i.e., ever since the last glacial maximum, there has been a general trend of increasing temperature, comprising well-documented palaeoclimatic and morphogenetic warming periods, separated by cooling periods. The most pronounced events occurred about 14,700 years and 11 to 12 thousand years ago. They have been documented by detailed Danish studies of Greenland ice cores (Cuffey & Clow, 1997; Alley, 2000; Vinther et al., 2009). The warming from about 11,700 years onwards deserves special emphasis. A few degrees increase in temperature over just 50 years and the accompanying rise in sea level have been documented. In the Polish literature, results of research on Lake Gościąż indicate the same time of exceptional palaeoclimatic events (Goslar, 1996). Interdisciplinary studies of Lake Gościąż have shown that the onset of the present interglacial (i.e., the Holocene) can be dated as such.

The last approximately 12,000 years initially were a period of clear warming, marking the onset of the current interglacial, then cooling (from ~11,000 to ~10,000 years) and finally the main Hol-

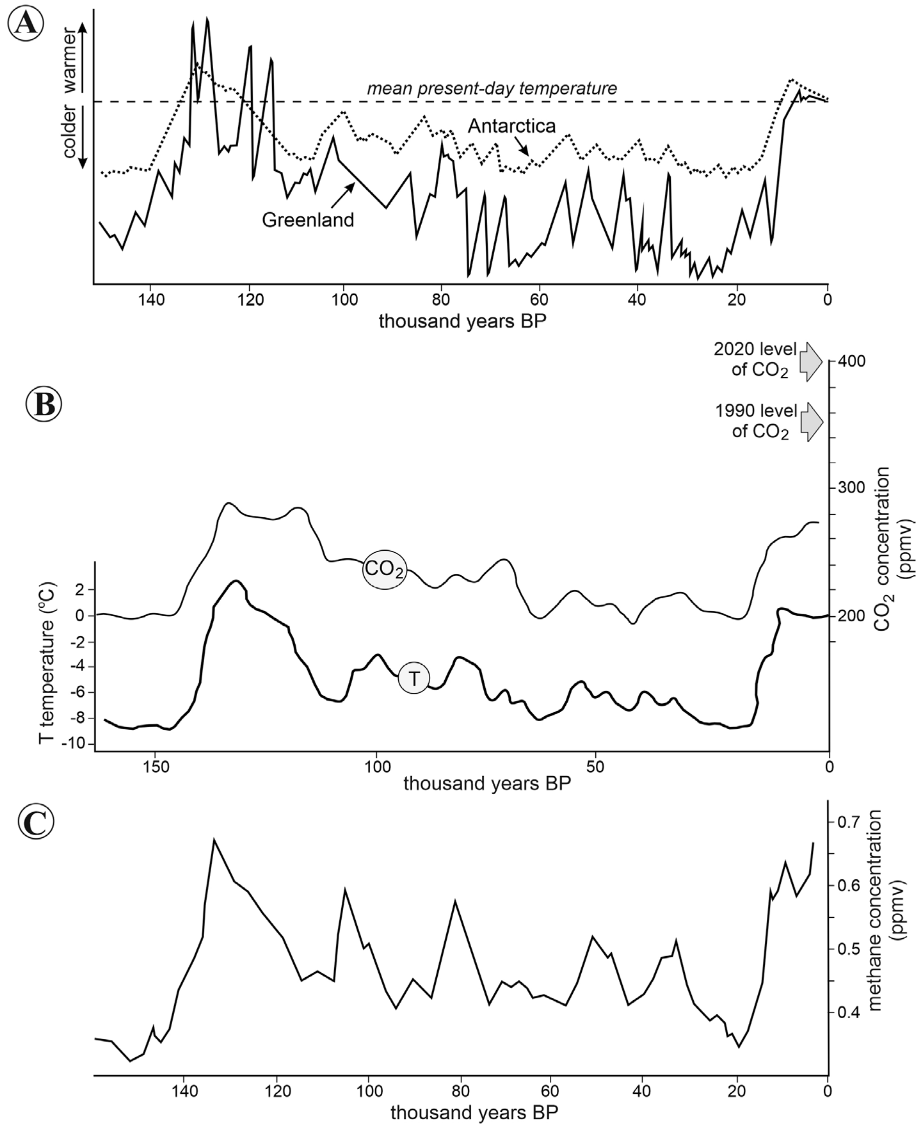

Fig. 8. A – Curves of temperature changes during the last ~150,000 years, based on analyses of ice cores from Antarctica and Greenland; **B –** Relationship between changes in CO_2 concentration and temperature; **C –** Changes in methane concentration (modified from Dawson (1992) and Houghton (2009)). Trends of Pleistocene temperature changes interpreted by ice core research have been confirmed and refined by data from marine sediment cores. Analyses of oxygen isotopes of planktic and benthic foraminifera from sediments of various climatic zones (research by N.J. Shackleton, N.D. Opdyke and C. Emiliani in the 1960s and 1970s) have allowed not only to confirm the general trends of temperature changes, but also to determine the stratigraphy of the so-called isotope stages.

ocene interglacial. Temperature changes also took place during this last period. Firstly, there was a slow increase in temperature for ~1,500 years, which led to the Holocene optimum (so-called Atlantic Period, lasting over 3,500 years). The last 5,000 years were initially characterised by moderate cooling, and for ~2,500 years there was a warming with some temperature fluctuations. By about 1300 AD, an early mediaeval warming event can be seen. Then, until about 1850 AD, there was a cold period, with a pessimum from the mid-17th to mid-19th centuries, known as the Little Ice Age. Since about the mid-19th century, there has been a positive temperature trend, referred to as 'global warming', but there is considerable controversy regarding the timing of its end.

The variability of temperature and concentration of gases in the atmosphere is conditioned by cyclical changes in solar activity and cosmic radiation reaching the Earth (Usoskin, 2017). The latter is easier during periods of solar activity minima, which is documented, for example, by an increase in the content of beryllium isotope (^{10}Be) recorded in ice cores. Solar minimum activity will occur in the second half of this century, which may result in thermal changes similar to those known as the 'Maunder' (1645–1717) and 'Dalton' (1790–1831) coldest phases of the Little Ice Age.

Apart from natural conditions, the Holocene also has an anthropogenic aspect. The multiple impact of man on the functioning of the natural environment is also clearly visible in the context of oxygen demand. Therefore, it seems justified that the term 'Anthropocene' has been introduced; this will be discussed further below.

Results of analyses of air bubbles from ice cores of Antarctica and Greenland, carried out at Princeton University and by Kazumi Ozaki (Tokyo Institute of Technology) and Charis Reinhard (Georgia Institute of Technology), mentioned above, indicate that during the last ~800,000 years (i.e., during most of the Quaternary) the oxygen content in the atmosphere decreased by about 0.7 per cent. A continuation of this trend will lead to excess of the level of oxygen concentration necessary for human life, in about 6.5 million years. Such a long time of oxygen depletion means that significant changes in oxygen content will still be possible, similar to what occurred during the ancient history of the planet. Calculations by the above-mentioned researchers contradict literature data on oxygen depletion, which will be discussed below.

The present-day composition of dry air at the surface of the globe (sea level) is considered to be stable, as follows: 78.08 per cent nitrogen, 20.95 per cent oxygen (negative trend), 0.93 per cent argon, 0.042 per cent carbon dioxide (upward trend), 0.002 per cent neon, 0.0005 per cent helium, 0.0002 per cent methane, 0.0001 per cent krypton and <0.0001 per cent xenon and radon. The proportions of the main components change in space and time. This also applies to oxygen, the amount of which is subject to daily, seasonal, annual and long-term, as well as geological and environmental fluctuations. Very important for the functioning of nature, but also for the existence of living organisms (including man), is the linear decrease in concentration relative to the height above sea level. For example, when at sea level the oxygen content is 20.9 per cent, then at an altitude of 1,219 m it is 17.9 per cent, 15.4 per cent at 2,438 m, 11.4 per cet at 4,877 m, 9.7 per cent at 6,096 m, 7.8 per cent at 7,925 m and 6.9 per cent at 8,830 m. There are also natural substances in the air (with spatially and seasonally variable contents; mineral dusts of weathering as well as volcanic and cosmic origin, plant pollen, salt particles) and numerous solid and liquid chemical compounds of industrial, transport (including rapidly growing air traffic), municipal, satellite flights, as well as progressive militarisation of the world.

Atmospheric air contains on average ~0.25 per cent of water vapour, the content of which decreases significantly in cold and very hot zones, while it increases to several percent in areas with a hot and humid climate.

Natural transformations of the entire system of nature are currently subjected to strong human impact (Waters et al., 2022). For a long time, human influence in environmental transformations had remained local. Over time, it took on a regional scope, and recently it has covered the entire globe. The scale of human impact justifies, despite existing controversies (Gibbard et al., 2022; Edwards et al., 2022), the introduction of a new time slice to the history of the Earth: the Anthropocene.

3. Human impact on changes in oxygen concentration

Human influence on the functioning of the natural environment has a long and varied history. It began with the invention of tools, and above all – the control of fire and preparation of hot food. The increasing impact on the environment has taken place in leaps and bounds, which are often referred to as 'revolutions'. These were successively: rock mining in the Palaeolithic and Neolithic, primitive metallurgy, agriculture and hydro-construction, urban development, as well as those with a global reach: development of industry, and presently – new technologies. These abrupt changes prompted Paul Crutzen (Nobel Prize in chemistry, 1995) to propose the term Anthropocene, the legitimacy of which was confirmed by Jan Zalasiewicz and Mark Williams (University of Leicester, UK) and Daniel Richter (Dreika University, USA) (Zalasiewicz et al., 2011). It seems that the start of the industrial revolution in the 19th century should be considered a time limit. In the 'period of coal and steam', global pressure of man on the environment began, as well as a rapid increase in oxygen consumption. While studying natural mechanisms, Alexander von Humboldt also took into account negative aspects of human impacts. He pointed out that industrially generated steam significantly affected the temperature of the atmosphere. Water vapour is the most important 'greenhouse gas', with an estimated percentage in excess of 25 per cent in the greenhouse process. Von Humboldt should therefore be regarded as the precursor of the view of anthropogenic intensification of global warming.

Man is considered to be the main cause of current global warming (see IPCC reports – Intergovernmental Panel on Climate Change). According to the author, contemporary trends in temperature changes are conditioned primarily by natural processes. Undoubtedly, man does intensify the existing trend, but in about 15 per cent. Such an estimate is supported by a comparative analysis of changes in the carbon dioxide content in the air, now and during the Atlantic Optimum of the Holocene (Wagner et al., 2002; Steinthorsdottir et al., 2013).

The increase in human impact, along with the onset of the Anthropocene, must be combined with the continuous increase in the demand for oxygen. Undoubtedly, this modifies the natural oxygen cycle. On the side of the formation of this gas necessary for life are photosynthesis (about 70 per cent of the effect) and plant photolysis, i.e., the breakdown of water molecules under the influence of light (about 30 per cent). On the natural oxygen consumption side are plant aerobic metabolism (using oxygen to generate energy) and plant photorespiration (using oxygen at night). In addition, other natural processes consume oxygen: carbonisation, hydration and hydrolysis, decomposition of organic matter in soils, dry rot (wood decay) and naturally occurring fires.

The distribution of sea and land areas (and differences in altitude on land), as well as the distribution of vegetation zones, cause fluctuations in the concentration of oxygen in the atmosphere. They are legible in daily, seasonal and annual rhythms (Kesling & Hertz, 1992; Daisuke et al., 2017). Seasonal fluctuations in the concentration of oxygen and carbon dioxide in atmospheric air, as well as general trends in these changes, have been extensively documented by measurements (Kesling & Hertz, 1992). One example is the outcome of б(O_2/N_2) and CO_2 measurements in Svalbard, where in 2012–2015 a trend of decreasing oxygen content and increasing carbon dioxide concentration was noted (Fig. 9).

The rhythmicity of oxygen concentration and the decreasing trend of oxygen concentration in the Earth's atmosphere are documented by twenty-five years of precision measurements from the Alert Station in Canada (Fig. 10; see Scripps Institute Oxygen Programme http://scrippso2.ucsd.edu/). They confirm the long-term tendency of natural phenomena, similar to the previously quoted results of analyses of air bubbles from cores of Greenland and Antarctic ice sheets. The decrease in O_2 concentration by ~0.7 per cent during the last ~800,000 years (i.e., almost the entire Quaternary)

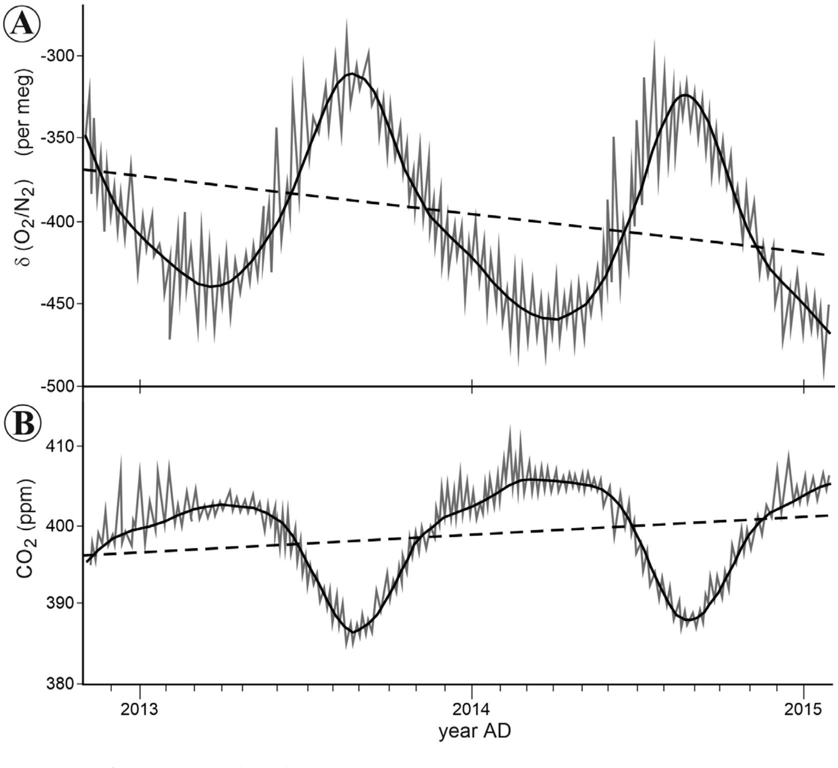

Fig. 9. Seasonal fluctuations of oxygen and carbon dioxide concentrations according to measurements from November 2012 to January 2015 at the Ny-Ålesund station, Svalbard. **A –** Fluctuations in oxygen content, with a generally decreasing trend; **B –** Fluctuations in carbon dioxide content, with a generally increasing trend (modified from Daisuke et al., 2017). Note the opposite rhythms of O and CO_2 concentrations.

is currently intensified by the technological use of oxygen by man.

Seasonal variabilities of oxygen content can be seen in various areas of the natural environment. Two examples illustrate this; firstly, the diffusion of gases to and from the atmosphere in the aeration zones of soil profiles (Jóźwiak, 2017). Temperature plays a decisive role in the variability of oxygen concentration, with secondary impact of humidity and atmospheric pressure. The maximum concentration of oxygen in soils (up to 20.0–20.9 per cent) occurs during the summer. The lowest is observed during the winter, from the end of December to the beginning/mid-February (usually ~17 per cent, but with temporary drops to <15 per cent, extremely to ~11 per cent). Secondly, there is temporal and spatial variability of oxygen concentration in the air of a large city and suburban area (Majewski & Cichocka, 2012). Changes in oxygen content in daily, monthly and annual rhythms have been analysed, as related to fluctuations in temperature, humidity and atmospheric pressure. Spatial differences in the distribution of O_2 concentration between the city centre and suburbs were clearly visible. The maximum oxygen content in the daily rhythm was recorded at night, and the lowest in the afternoon (around 4 pm). As a rule, the oxygen content was lower in the city centre than in the suburbs. In addition, the centre recorded the greatest short-term fluctuations in oxygen content, even on a health-threatening scale. Some annual differences in oxygen rhythms were also found, but the short period of measurements does not allow for reliable generalisations. Nevertheless, changes in oxygen content in the air of a large agglomeration are important for understanding oxygen issues within the context of the nature-human system, which will be discussed further below.

The system of nature, with its atmosphere fundamental to the existence of mankind, is subject to growing human impact. The use of oxygen is increasing intensively. This forces us to think about providing oxygen for civilisation. As documented by precise measurements, the reduction of this life-giving gas has been estimated by using a stochastic nonlinear model (Martin et al., 2017). This new mathematical model shows that under biogeochemical interactions, an oxygen decline will be reached much sooner than previously estimated. It predicts that the oxygen in the atmosphere will reach zero in about 4,400 years. It is probable that the oxygen content necessary for human life, i.e., at a stable concentration level, not less than 15 per cent, will be reached in about 3,600 years. The end of the oxygen atmosphere of the Earth will occur around the year 6000. These are dividing lines clearly shorter than those indicated, for example, by NASA experts K. Ozaki and Ch. Reinhard, as stated above. As cam be seen, the time limits of atmospheric oxygen depletion elaborated in the scientific literature are characterised by a huge range.

Regardless of whether de-oxygenation will be rapid or there will be another oxidative turn, the end of the oxygen atmosphere will come one day. A complete lack of oxygen will be preceded by the demise of aerobic organisms. Human civilisation will cease to exist. In the record of environmental changes of the globe, traces of the Anthropocene will remain, which was suggestively presented in the book by Zalasiewicz et al. (2011). During the current Anthropocene, it is necessary to take reasonable care of the functioning of civilisation in all areas of human-environment interaction.

Civilisation development, even its survival, is not possible without interfering with the natural environment, including a constant use of oxygen. Since man mastered fire, the demand for oxygen has steadily increased. A leap in the use of oxygen occurred already during the erection of megalithic structures (Michalski, 2003). Too little is known

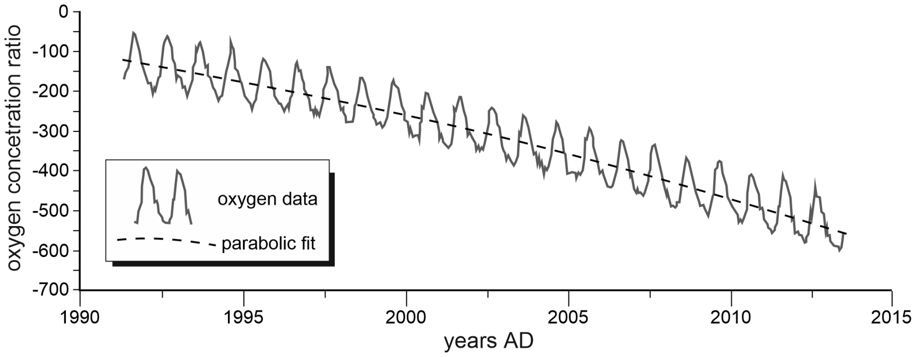

Fig. 10. Seasonal rhythms of changes in oxygen concentration between 1992 and 2013, according to measurements at the Alert Station in Canada and the general decreasing trend (after Martin et al., 2017).

about that period. There is no doubt that tools produced by fire were in use at that time. Man used fire wisely already in the early Palaeolithic. However, during the Neolithic there was a technological breakthrough. Copper (~3,800 BC) and bronze (~3,500 BC) were smelted, and thus primitive metallurgy began. At the same time, the brick firing method began (~3,500 BC). The technique of obtaining tar was mastered very early. It should be added that long before that, natural bitumens or mixtures of hydrocarbons were used. This is evidenced by the biblical descriptions of the construction of the Ark (sealing its structure) or the erection of the Tower of Babel (bonding with bricks). It is worth mentioning the scientifically documented great constructions, such as the Ziggurat in Ur – the archaeological site of Tell al-Muqajjar with the so-called 'Tar Hill'. Already in the Neolithic, the process of deforestation started, which has intensified constantly. The demand for wood, together with the need to acquire new areas for agriculture, resulted in a reduction in oxygen generation. The technological use of fire affected the environment first locally and then regionally. Starting with the 19th-century 'industrial revolution', human impact reached global scales. Currently, this is especially visible in the era of the 'technological revolution', i.e., from the mid-twentieth century.

In the light of the author's palaeoclimatic knowledge, the current trend of ongoing global warming is primarily a manifestation of natural fluctuations of the current interglacial. It can be concluded from temperature curves (Fig. 8) that the Holocene optimum has been exceeded. This may have occurred during the Atlantic period (about 5 to 7 thousand years ago). The natural trend of the current decrease in average temperature is disturbed by man, resulting in the extension of the temperature optimum in the form of a warm peak 'plateau'. This is well reflected in albedo changes, most noticeable in the northern hemisphere. The rise in temperature is most pronounced in high latitude areas. Ice covers on land and seas are rapidly disappearing, reducing the reflection of the sun's rays. This causes permafrost to disappear, releasing carbon dioxide and methane. At the same time, the solar energy reaching the globe is intercepted by the oceans. More than 70 per cent of atmospheric oxygen production comes from the oceans, as a result of plankton, as well as the activity of algae and some bacteria. It should be added that the intensity of photosynthesis is subject to spatial and temporal changes (seasonal and even daily). The oxygen generated is simultaneously consumed by marine organisms. In addition, the increasing pollution of the oceans hinders photosynthesis. Warning signs of increasing pollution of ocean waters, hindering photosynthesis, were already reported in the 1950 and 1960s by Thor Heyerdahl, after his spectacular expeditions on the Kon-Tiki raft and the Ra boat. Since then, the degradation of marine environments has intensified, as evidenced by a gigantic 'trash island' in the Pacific Ocean. All these factors cause that local zones in the oceans consume more oxygen than they produce. As a consequence, hypoxia occurs, which is sometimes referred to as 'dead zones'.

Growing thermal contrasts result in an increase in extreme supernormal phenomena all across the globe. There are extreme rainfalls and periods of prolonged drought. Disturbances in vegetation processes contribute to the reduction of plant resistance to various harmful effects (e.g., susceptibility to fires), which results in limiting oxygen emissions.

Vegetation zones that guarantee oxygen supply are concentrated in three bands: equatorial forests, temperate forests and polar taiga. Having been destroyed for centuries, forests are still subject to degradation, which reduces the supply of oxygen. Particularly acute is the constant reduction of equatorial forest complexes, largely due to fires. As a result of changes in the Earth's thermals and air pollution, the vegetation of the taiga zone clearly loses its biological resistance, becoming susceptible to more and more frequent fires. Heavily damaged forests of the temperate zone are not everywhere rebuilt or even properly protected. It should be remembered that forests provide oxygen to the atmosphere only in the phase of vegetative activity. Dead trees become oxygen consumers. Thus, proper forest management, with optimum felling, makes not only economic, but also environmental sense. The geological history of changes in oxygen concentration confirms the need to care for high-growing vegetation. The double increase in atmospheric oxygen content mentioned here, was associated with the intensive development of plant biocoenoses. The imperative of the present time is proper forest management, as implemented by Polish foresters.

It must be said that man uses atmospheric oxygen more and more intensively, while contributing to the increasing exploitation of the natural environment. Currently, there is no technology or field of life that does not require this gas. Some examples of human-nature interaction will illustrate this.

A matter of transport (by land, sea and air): combustion engines, which dominate transport, not only 'consume' oxygen, but also emit gaseous and solid pollutants. Particularly unfavourable for the natural environment has been the intensive development of aviation on the border of the troposphere and stratosphere, as well as supersonic and hypersonic devices operating at even greater heights. Reducing exhaust emissions is absolutely necessary. Hence the postulated and implemented transition to the so-called 'electromobility' or 'hydromobility'. Unfortunately, they also cause negative effects on the natural environment. In order to obtain energy, it is necessary to maintain natural resources, which are often scarce. They will run out in a few decades (Łuszczyk, 2021; Brożyna & Kozioł, 2014). It is also necessary to produce devices that need to be disposed of after a relatively short period of use. A side effect of all these energy-consuming activities is the intense consumption of oxygen.

Meeting civilisation's energy needs requires the creation of a diversified system of carriers. A properly organised energy system must operate with emission-free installations and generators with continuous power stability. It is necessary to take care of continuous reduction of the troublesomeness of the entire system for the environment.

It is impossible to meet the entire energy demand by switching to the so-called emission-free energy. Both wind farms and solar installations do not guarantee uninterrupted energy supply. Moreover, they are also harmful to the environment. Solar installations become 'heat islands'. This applies mainly to large-area farms, usually built directly on the ground, which excludes the soil from its natural functioning. To a much lesser extent, this applies to urban areas with dispersed photovoltaic cells. Nuclear power plants, considered emission-free, ensure the durability of energy supplies, but they are troublesome for the environment during their construction, and especially during the disposal of used fuel. In addition, they pose a potential threat during possible failures, and above all during war or terrorist incidents. Gas-fired power plants, ensuring a stable supply of energy, have a relatively weak impact on the atmosphere. Coal-fired power plants, on the other hand, emit a lot of gas and dust pollutants into the atmosphere. Fossil-fuel power plants pose a methane threat to the natural environment.

An important and still underutilised source of energy is the heat of the Earth. The inexhaustible resources of geothermal (heat of solutions) and geothermics (heat of rocks) should become more and more widely used. This is justified by unlimited resources, local nature of the installation (eliminating long-distance energy transmission and its high losses), limiting the area without power supply due to possible technological failures, random events or terrorist and war events.

The current state of science and technology allows to increase the energy use of the Earth's heat. This is possible due to equipment and exploitation possibilities: drilling techniques, experience in the field of rock fracturing in the extraction of shale gas and the use of binary technologies, create the possibility of even building power plants, also outside areas with a favourable geothermal degree.

All energy-producing technologies are consumers of oxygen, both during the construction and disposal of installations, as well as their energy production. It seems that the energy use of the Earth's heat is not only relatively harmless to the environment, but also the least oxygen-consuming among other power plants.

Atmospheric oxygen should be used only to the extent necessary for the functioning of societies. It is absolutely necessary to refrain from consuming oxygen in cases such as 'orbital and extra-orbital tourism'.

The most oxygen-consuming (thereby completely ignoring the principles and requirements of ecology) is growing militarisation of the world, which assumes the hallmarks of collective madness, which can lead to the destruction of the natural environment and a great extinction. It must be unequivocally stated that the negative impact of the militarisation of the Anthropocene, encompassing the Earth's lithosphere and outer space, probably exceeds half of the total negative human impact on the natural environment. It is also the largest consumer of oxygen.

4. Conclusions

- Unique in the Solar System, the Earth's oxygen atmosphere began to form perhaps as early as 2.5 billion years ago. Most likely, however, its intensive development took place during the last billion years, with the appearance of numerous multicellular organisms. Probably the fully developed atmosphere has existed for 0.6 billion years, which, in terms of geological time, is a relatively 'short' period in the history of the globe.
- In the history of the atmosphere, there have been periods of both increasing and decreasing oxygen levels. These fluctuations were determined by a combination of natural phenomena: astronomical and climatic, tectonic and volcanic, as well as extraterrestial, i.e., impact-derived. The feedbacks, positive and negative, affected biological processes. The biological factor should be assigned a major role in changes in oxygen content of the air.

- Since at least the middle of the Quaternary (less than *c.* 800,000 years ago), there has been a trend of continuous depletion of oxygen in the atmosphere. The existence of this negative trend seems to indicate a rapid (in the sense of the history of nature on Earth) end to the oxygen atmosphere. It is estimated that the time to reach the lower threshold of oxygen content, necessary for human life, is expected to occur very quickly. Regardless of the correctness of these assessments, oxygen must not be wasted unnecessarily by the human community.
- The existence of the human community depends on the amount of oxygen in the atmosphere. On the other hand, the functioning of civilisation is based on the use of energy. For this purpose, it is necessary to use various energy sources in order to reduce (even eliminate) the negative impact on the natural environment. This applies primarily to the demilitarisation of the world, as well as the cessation of individual air flights and space tourism. There is no technology with zero environmental harm. The least burdensome for the environment (and comsuning the least oxygen) are technologies that use the heat of the Earth.

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