GLOBAL WARMING AND OTHER CLIMATE CHANGE PHENOMENA ON THE GEOLOGICAL TIME SCALE

by

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Global warming and other climate change phenomena became a worldwide exploited subject over recent decades. World science has made enormous progress in understanding past climate change and its causes, and continues to study current and potential impacts that will affect people in the future. All scientists agree that the Earth's climate is changing due to natural phenomena, and most of them argue that human activities are increasing the greenhouse effect, while some scientists attribute climate changes exclusively to the natural causes. Though there still is, and always will be, need for multiple lines of research on an extremely complex system like Earth's climate is, an immediate consensus is crucial for decision-makers to place climate change in the context of other large challenges facing the world today. This paper discusses the existing body of evidence on climate changes in the past, and uncertainties that prevent scientists to reach full consensus on how climate might change in the future. It extends the time scale of climate changes over the entire history of Earth to help better understanding of hypothetical changes and their consequences that could be expected both in the near and in a very distant future.

Key words: *global warming, climate change, energy balance, greenhouse effect*

Introduction

It is well known that the existing life on Earth is enabled by natural greenhouse effect of the atmosphere, which keeps the mean surface temperature around 33 °C higher than it would otherwise be (without this effect the temperature would be –18 °C instead of +15 °C at present). This is due to the greenhouse effect of the atmosphere, containing GHG such as water vapour, CO_2, CH_4, and N_2O. These GHG allow the Sun's rays to reach the Earth's surface and keep the heat they create from escaping into space. By blocking a part of reflected radiation from escaping to space, the GHG control the way natural energy flows through the climate system on Earth. If the established energy balance is disturbed, the climate system reacts so that the mean temperature increases (global warming) or decreases (global cooling).

Scientists generally define the five components of Earth's climate system to include atmosphere, hydrosphere, cryosphere, lithosphere (the surface soils, rocks, and sediments), and biosphere. Particular interests of the climate science are focused on a sustained rise in the greenhouse effect due to a fast increase in atmospheric concentrations of trace gases (CO_2, N_2O, CH_4) and on the climate sensitivity in response to the sum of climate forcings, such as thermohaline circulation (hydrosphere), life (biosphere), land-ocean-atmosphere thermodynamics, carbon cycle, *etc*.

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Climate change, as an extremely complex phenomenon with many challenging implications, is the subject of an extensive body of interdisciplinary science, so that a great deal is known about the climate system. The scientists discovered that the Earth's climate is always changing and that many factors influence the temperature of the globe to change (increase or decrease) due to various natural phenomena such as changes in the Earth's orbit, biotic processes, variations in solar radiation received by the Earth, volcanic eruptions, oceanic and orogenic changes due to plate tectonics, as well as the natural changes in atmospheric concentration of GHG. Besides, the human activities have been identified as primary causes of ongoing climate change, often referred to as *global warming*.

The most general definition of climate change is *a change in the statistical properties (principally its mean and spread) of the climate system when considered over long periods of time, regardless of cause* [1]. Accordingly, fluctuations over periods shorter than a few decades, such as El Niño, do not represent climate change. Within scientific journals, *global warming* usually refers to surface temperature increases, while *climate change* includes global warming and everything else that increasing GHG emissions might affect [2]. This switch in terminology to *climate change* was to emphasise that the change in the composition of the Earth's atmosphere could result in a variety of extreme weather events, not just warming. The World Meteorological Organization proposed the term *climatic change* to encompass all forms of climatic variability on time-scales longer than 10 years. The noun *climate change* was then incorporated in the title of the Intergovernmental Panel on Climate Change (IPCC) and in the UN Framework Convention on Climate Change (UNFCCC). The UNFCCC claims that *Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over comparable time periods* [3].

Scientists actively work to better understand past and future climate by using observations and theoretical models. Their climate record is based on geological evidence from borehole temperature profiles, cores removed from deep accumulations of ice, floral and faunal records, glacial and periglacial processes, stable-isotope and other analyses of sediment layers, as well as from records of past sea levels. More recent data are provided by the instrumental record. General circulation models, based on the physical sciences, are often used in theoretical approaches to match past climate data, make future projections, and link causes and effects in climate change.

As the scientists observed that the Earth is warming, the ice is melting, and sea level is rising, a majority of them (97% [4]) agree that the human (anthropogenic) activities are the cause of these changes. The ability of natural and anthropogenic emissions of the GHG to trap heat is regarded as firmly established science. Although there is a consistent objective evidence that humans are changing the climate on Earth to a considerable extent, many climate change sceptics deny this evidence and call for reconsidering the predictions reported by the IPCC and majority of other scientists, who attribute global warming and other signs of climate change to the increase of concentration of GHG in the atmosphere due to human activities [5]. Nevertheless, scientific conclusions on climate change have been accepted by most of scientific community, although a large number of uncertainties remains, which feed scepticism on the human impacts on global climate [6].

Evidence for climatic change is taken from a variety of sources that can be used to reconstruct past climates. Reasonably complete global records of surface temperature are available beginning from the mid-late 19^{th} century. For earlier periods, most of the evidence is indirect, and the climatic changes are inferred from changes in indicators that reflect climate, such as vegetation, ice cores, tree rings (dendrochronology), sea level change, and glacial geology. Climate change in the recent past may be detected by corresponding changes in settlement and agricultural patterns, as well as be understood from the archaeological evidence, oral history and historical documents. For longer term, however, much wider insights into the past climate changes are necessary, going back beyond the history of humankind and climate changes that may have been linked to the collapse of various civilizations [7].

This paper discusses the existing body of evidence on climate change, taking into account both, natural and anthropogenic causes, as well as what facts still remain to be clarified to enable the climate change science be based on a multitude of well-established theories. In section *Historical climatology*, common short-term studies focused on the historical changes in climate and their effect on human history and development, section are presented. Paper encompasses climate changes over the entire history of Earth in section, *Paleoclimatology*, in order to compensate the indispensable link with the prehistorical climate events and to, better understand possible future changes, finally presented in section *Projected climate changes in the future*.

Historical climatology

Scope and background

The researchers who deal with the Historical climatology have documented changes in surface, atmospheric, and oceanic temperatures, as well as melting of glaciers, diminishing of snow cover, shrinking of sea ice and rising sea levels, acidification of oceans and increasing atmospheric water vapor. For example, global annually averaged surface air temperature has increased approximately by 1 °C over the last 115 years (1901-2016) period, found to be the warmest in the history of modern civilization, while the global average sea level has risen by about 2 cm since 1900, with a rate of rise greater than during any preceding century in at least 2,800 years [8]. Heavy rainfall is increasing in intensity and frequency and is expected to continue to increase. Heat waves have become more frequent since the 1960's, while extreme cold temperatures and cold waves are less frequent.

It was suggested by scientists that humans emit CO_2 10,000 times faster than natural processes have done in the past [9]. They claim that there is a close correlation between CO_2 and temperature, where CO_2 has a strong control over global temperatures [10] and that continued rising levels of CO_2 are already changing the climate. Currently, anthropogenic GHG are accumulating in the atmosphere, which is believed to be the main cause of global warming because the increased atmospheric CO_2 concentrations have been linked to driving or amplifying increased global temperatures. Observations show that global temperatures on the Earth have risen about one degree Celsius since the industrial revolution, fig. 1 [11]. Figure 2 shows that the atmospheric concentration of CO_2 reached 407 parts per million (ppm) by volume during the year 2017 [12], and continues to rise.

Natural changes in the climate system include the changes in ocean-atmosphere circulations, which can affect the global average surface temperature by redistributing heat between the deep ocean and the atmosphere and/or by altering the cloud/water vapor/sea ice distribution, as well as the total energy budget of the Earth. The Earth's atmospheric circulation is the large-scale movement of air, and, together with ocean circulation, is the means by which thermal energy is redistributed on the surface of the Earth. From the point of view of the laws of thermodynamics, it can be viewed as a heat engine ([13]) driven by the Sun's energy, and whose energy sink is the blackness of space. The work produced by that *engine* causes the motion of the masses of air and, in that process, it redistributes the energy absorbed by the Earth's surface near the tropics to space by winds, ocean currents, and other transfer mechanisms, thus affecting the

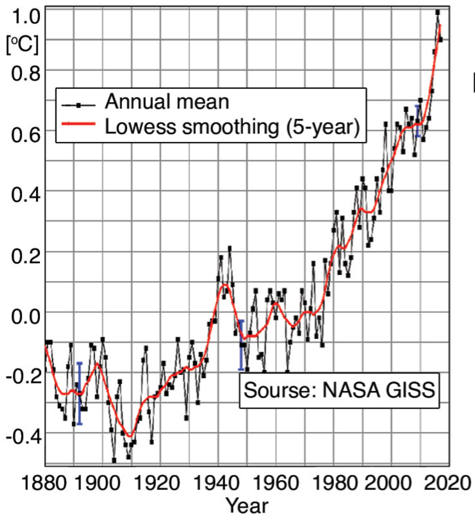

Figure 1. Global mean temperature anomaly [11]

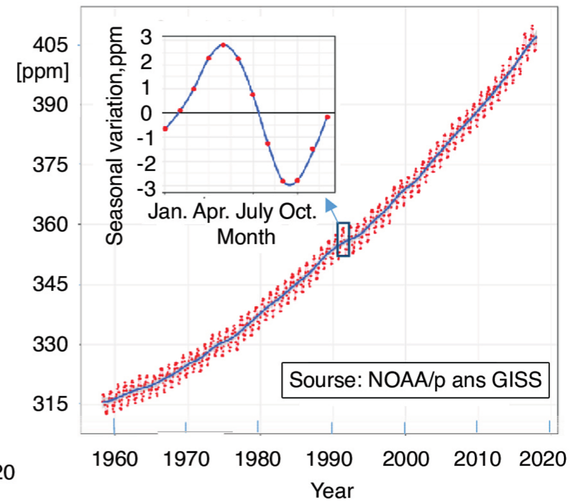

Figure 2. Monthly mean CO_2 concentration [12]

climate of different regions, including the latitudes nearer the poles. The rate at which energy is received from the Sun and the rate at which it is lost to the space determine the equilibrium temperature and the climate of the Earth.

Climate forcings

Understanding current global warming and other phenomena of the climate change requires understanding the changes in the factors that shape the climate (*climate forcings* or *forcing mechanisms* [14]). Climate forcings include processes such as variations in solar radiation, variations in the Earth's orbit, variations in the albedo or reflectivity of the continents, atmosphere, and oceans, mountain-building and continental drift, as well as changes in GHG concentrations. Also, there are a variety of climate change feedbacks that can either amplify or diminish the initial forcing. Some parts of the climate system, such as the oceans and ice caps, respond more slowly in reaction to climate forcings, while others respond more quickly. There are key threshold factors which, when exceeded, can produce rapid change of the climate on the Earth [15].

Forcing mechanisms can be either *internal* or *external*. Internal forcing mechanisms are natural processes within the climate system itself (*e.g.*, the thermohaline circulation), while external forcing mechanisms can be either natural (*e.g.*, changes in solar output, the Earth's orbit, volcano eruptions) or anthropogenic (*e.g.* increased emissions of GHG and dust). Whether the initial forcing mechanism is internal or external, the response of the climate system might be fast (*e.g.*, a sudden cooling due to airborne volcanic ash reflecting sunlight), slow (*e.g.* thermal expansion of warming ocean water), or a combination. Therefore, the climate system can respond abruptly, but the full response to forcing mechanisms might not be fully developed for centuries or even longer [15].

Predominant source of energy input to the Earth is the radiation from the Sun (other sources include geothermal energy from the Earth's core, tidal energy from gravitation by the Moon and heat from the decay of radioactive compounds). The climate forcing may be regarded as the difference of radiant energy received from the Sun and the outgoing long-wave radiation from the Earth's surface back to the space. Earth radiative balance is dependent on the insolation and the concentrations of GHG and aerosols, and, dependent on the radiative balance of incoming and outgoing energy, the Earth either warms up or cools down. Slight variations in Earth's motion lead to changes in the seasonal distribution of sunlight reaching the Earth's surface, and how it is distributed across the globe.

There is very little change to the area-averaged annually-averaged sunshine, but there can be strong changes in the geographical and seasonal distribution. These changes include positive forcing from increased GHG, negative forcing from increased sulfate aerosols and forcings from indirect aerosol feedbacks, as well as minor contributions from solar variability and other factors [16]. Also, there are many uncertainties about the scale and impacts of climate change, particularly at the regional level, because of a limited possibility of climate models to simulate complex processes and their mutual interactions and feedbacks [6]. For example, due to both limited understanding of how aerosols interact with the atmosphere and of their reference concentrations during the pre-industrial period, it is not sure that the predictions of future trends could reach a required high level of confidence.

The change of climate is mainly attributed (directly or indirectly) to human activity, altering the composition of the global atmosphere. Human activity includes the pollution that arises from industrial activity and other sources that produce GHG which have the ability to absorb the spectrum of infrared light and contribute to the warming of the atmosphere. Once produced, these gases can remain trapped in the atmosphere for tens or hundreds of years [17]. The lifetime of CO_2 in the atmosphere cannot be represented with a single value because it moves among different parts of the ocean-atmosphere-land system, thus creating the life enabling carbon cycle. Some of the excess CO_2 is absorbed by natural processes, but some remains in the atmosphere for thousands of years, due to the slow process by which carbon is transferred to ocean sediments [18]. Because of the delaying effect of the oceans, surface temperatures do not respond immediately to GHG emissions, so that climate change will continue for hundreds of years after atmospheric concentrations have stabilized.

The Earth's climate system is very sensitive to any disturbance within the ocean-atmosphere-land chain and particularly to changes of the concentration of the GHG in the atmosphere. The ratio of the annual increase in atmospheric CO_2 compared to CO_2 emissions from burning fossil fuels and cement manufacturing (called the *airborne fraction*) has been around 60% since the 1950's, indicating that about 60% of the new CO_2 in the atmosphere each year originated from human sources [19]. For clarity, this is not meant to suggest that 60% of the uptake of CO_2 into the atmosphere comes from human activity, but it means that the atmosphere exchanges around 210 Gt of carbon annually, and absorbs between 6 and 10 Gt more than it loses (of this net gain, about 60% is attributable to the burning of fossil fuels [20]). The ever increasing emissions from burning fossil fuels fig. 3 [21]) are the major contributor to the overall radiative forcing, as evident from fig. 4, based on a series of averaged data for the year 2005 [22].

Taken together, the forcings from different sources during the year 2005 resulted in a net increase in radiative forcing on the Earth surface by about 1.6 W/m^2. The IPCC claims that the GHG emissions have already risen since and disturbed the net global energy budget by change in radiative forcing by about 70% (1.82 W/m^2 of the 2.63 W/m^2 [23]). Because different forcings can interact to either amplify or interfere with each other, it is not possible to simply sum the radiative forcing contributions from particular sources and obtain a total forcing. For example, in the case of GHG, two different gases may share the same absorption bands, thus partially limiting their effectiveness.

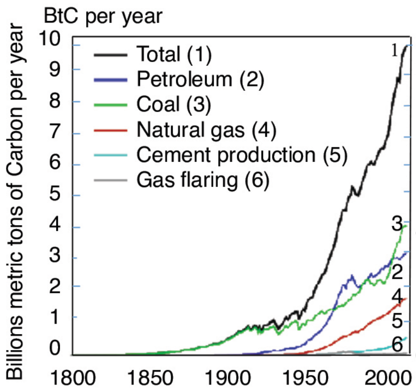

Figure 3. Global fossil carbon emissions [21]

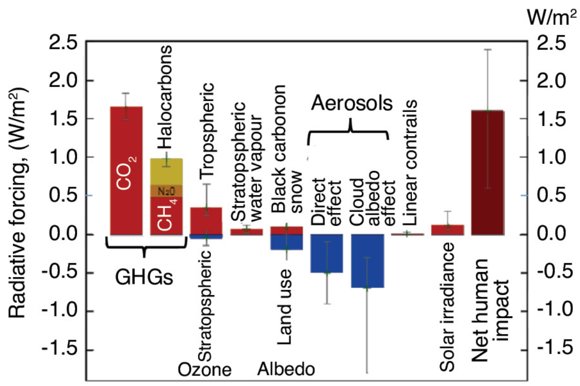

Figure 4. Global mean radiative forcing in 2005 [22]

Atmospheric concentrations of major GHG

The atmosphere is one of the Earth's major carbon reservoirs and an important component of the global carbon cycle, holding approximately 720 Gt of carbon [24]. The CO_2 is an integral part of the carbon cycle, in which carbon is exchanged between the Earth's oceans, soil, rocks and the biosphere. As the use of carbon by humans is a very new dynamic on a geological time scale, it is important to be able to track sources and sinks of carbon in the atmosphere. One way of doing so is by observing the proportion of stable carbon isotopes present in the atmosphere. There are two stable isotopes of carbon in sea water: carbon-12 (^{12}C) and the rare carbon-13 (^{13}C), which makes only 1.11% of carbon atoms [25]. Biochemical processes, including photosynthesis, incorporate the lighter ^{12}C isotope more readily than heavier ^{13}C ([26]) and, therefore, an ocean with photosynthetic life will have a lower $^{13}C/^{12}C$ ratio within organic remains. Because fossil fuels originate mainly from plant matter, the $^{13}C/^{12}C$ ratio in the atmosphere falls when large amounts of fossil fuels are burned, releasing ^{12}C. Conversely, an increase in the $^{13}C/^{12}C$ ratio in the atmosphere suggests a higher biospheric carbon uptake [27].

The atmospheric concentration of CO_2 was around 280 ppm during the 10,000 years up to the mid-18th century [28], but the concentration has increased by more than 45% since the start of the Industrial Revolution [23]. The major part of this increase has been attributed to human activities, particularly to burning of fossil fuels and deforestation. This increase of CO_2 and other GHG in Earth's atmosphere (of which water vapor is by far the most abundant) has produced the current episode of global warming. About 30-40% of the CO_2 released by humans into the atmosphere dissolves into oceans, rivers and lakes [23].

Following the start of the Industrial Revolution, atmospheric CO_2 concentration has increased to over 400 ppm and continues to increase, causing the phenomenon of global warming. The daily average concentration of atmospheric CO_2 at Mauna Loa Observatory first exceeded 400 ppm on May 10, 2013 ([29]), although this concentration had already been reached in the Arctic in June 2012 [25]. The CO_2 currently constitutes about 0.041% by volume of the atmosphere [8], which corresponds to approximately 3,200 Gt of CO_2, containing approximately 870 Gt of carbon (each ppm of CO_2 in the atmosphere represents approximately 2.13 Gt of carbon). The global mean CO_2 concentration is currently rising at a rate of approximately 2 ppm per year and accelerating [30]. There is an annual fluctuation of about 3-9 ppm ([31]), which is negatively correlated with the growing season (concentrations in the Northern Hemisphere reach a peak in May and decline to a minimum in October, fig. 2, near the end of the growing season [8]).

The CH_4 is 25 times more potent GHG than CO_2 [5, 17]. Because it reacts fairly quickly with other compounds, and does not stay in the atmosphere as long as CO_2 (atmospheric lifetime of CH_4 is about 8 years [32]), the atmospheric concentration of CH_4 is relatively low (CH_4 levels have risen gradually from about 0.700 ppm in 1750 to 1.775 ppm in 2005 [33]), it plays a secondary role in the greenhouse effect. The amount of CH_4 produced and absorbed yearly varies widely. Natural production of CH_4 accounts for 10-30% of global CH_4 sources, while more than 70% of atmospheric CH_4 comes from biogenic sources [34]. Anthropogenic CH_4 is produced by raising cattle and through the decay of biodegradable waste in landfills, as well as by different industrial processes, including mining of the fossil fuels [21].

Temperature fluctuations

The global temperature record shows the fluctuations of temperature of the atmosphere and the oceans through various spans of time. The most detailed information exists since 1850, when methodical thermometer-based records began. For the lower troposphere, a global average trend since 1978 was about +0.15 °C per decade ([32]) by 2005, and later increased to +0.20 °C per decade [35].

Proxy reconstructions extending back 2,000 years have been performed, but those for the last 1,000 years are supported by more and higher quality independent data sets. To reconstruct the earlier temperatures, evidence such as tree ring widths, coral growth, isotope variations in ice cores, ocean and lake sediments, cave deposits, fossils, ice cores, borehole temperatures, and glacier length records are correlated with climatic fluctuations. Figure 5, which compares ten reconstructed proxy temperature studies covering last 2,000 years, shows that there was a Medieval Warm Period between about 800 and 1300 AD followed by a Little Ice Age which ended about the mid-19th century [36].

The Little Ice Age may be considered to have been initiated by variation in solar radiation ([37]), but the cyclical change of the Sun's energy output is not yet fully understood. It differs from the very slow change that is happening within the Sun as it ages and evolves. Solar output varies on shorter time scales, including the 11-year solar cycle, and longer-term modulations [38]. Some scientists claim that the solar radiation increases from cyclical sunspot activity affecting global warming, so that climate may be influenced by the variation in the solar output, combined with the human-induced and other radiative forcings. Variations in solar activity during the last several centuries, based on studies of sunspots and beryllium isotopes from dust found in ice cores, is shown in fig. 6. The level of beryllium-10 (^{10}Be) has been shown to closely match with the solar activity measured by the number of sunspots [39]. Concentration of ^{10}Be is presented as the ratio to daughter isotopes, which have been produced by cosmic rays in the atmosphere, absorbed into the hydrological cycle and deposited in ice cores. It is

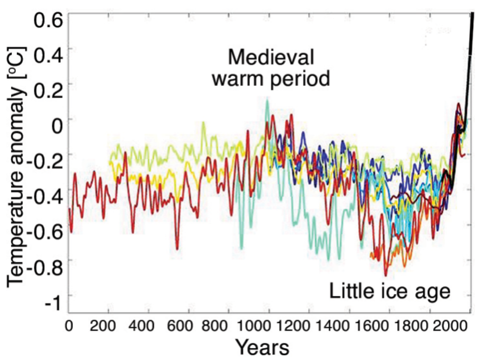

Figure 5. Temperature anomaly over last 2 millenia [36]

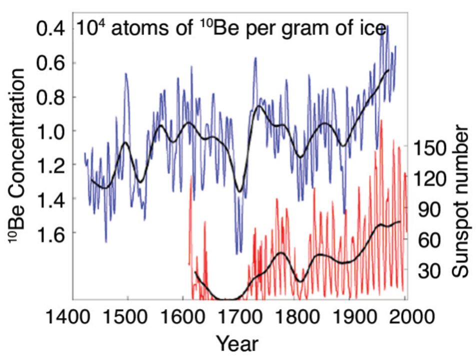

Figure 6. Sunspots and ^{10}Be concentration [39]

evident that the period of Little Ice Age from 1500's to 1800's, which was marked by relative cooling and greater glacier extent than the centuries before and afterward ([40]) is in close correlation with an extraordinarily small number of sunspots, known as *Maunder minimum* [41].

Ocean circulation

Alterations to ocean processes such as thermohaline circulation play a key role in redistributing the heat in the oceans, fig. 7 [42]. The oceanic aspects of these circulations can generate variability on centennial time scales due to the ocean having hundreds of times more mass than in the atmosphere, and thus very high thermal inertia. For example, due to the long time scales of the oceanic circulation, ocean temperature at depth is still adjusting to effects of the Little Ice Age, which occurred several centuries ago.

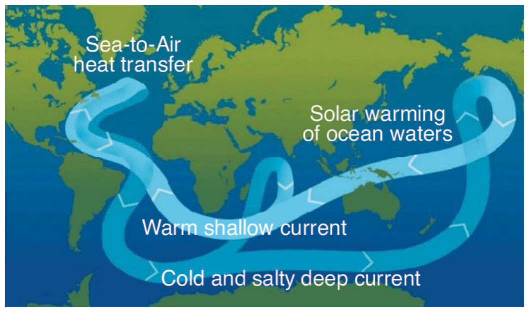

Figure 7. Schematic of thermohaline circulation [42]

The locations of the seas are important in controlling the transfer of heat and moisture across the globe, and therefore, in determining global climate. The position of the continents determines the geometry of the oceans and thus influences patterns of ocean circulation.

Over the course of millions of years, the motion of tectonic plates reconfigures global land and ocean areas and can affect both global and local patterns of climate and atmosphere-ocean circulation. According to recent studies, global-mean sea level rose by 195 mm during the period from 1870 to 2004, and since then, as satellite-based records indicate, there has been a further 43 mm of global-mean sea levels rise, as of July 2017 [43].

Volcanic emissions

The effects of volcanic emissions of carbon and sulfur oxides are of particular importance when natural causes of climate change are considered. The CO_2 emissions including amounts released from midocean ridges, volcanic arcs, and hot spot volcanoes, are estimated to be at a much lower level than the effects of current human activities. Humans generate 100-300 times the amount of CO_2 from volcanoes ([44]), so that the annual volcanic emissions of CO_2 are the equivalent of only 3 to 5 days of human-caused output.

Due to the optical properties of SO_2 and sulfate aerosols, they strongly absorb or scatter solar radiation, creating a global layer of sulfuric acid haze. The volcanic emissions of SO_2, considered to be large enough to affect the Earth's climate for more than one year, are the ones that inject over 100,000 tons of SO_2 into the stratosphere [45]. On average, such eruptions occur several times per century, and cause cooling (by partially blocking the incoming solar radiation to the Earth's surface) for a period of a few years (the Mount Tambora eruption in 1815 caused 1816 the *Year without a summer* [46]). Small eruptions, with emissions of less than 100,000 tons of SO_2 into the stratosphere, impact the atmosphere only subtly, as temperature changes are comparable with natural variability. However, because smaller eruptions occur at a much higher frequency, they can equally have a significant impact on the atmosphere.

Paleoclimatology

Scientific basis

The science of Paleoclimatology studies the changes in climate taken on the scale of the entire history of Earth. It uses a variety of proxy methods from the Earth and life sciences to obtain data previously preserved within rocks, sediments, ice sheets, tree rings, corals, shells, microfossils and elsewhere. The scientific study field of paleoclimate began to form in the early 19th century, when discoveries about glaciations and natural changes in Earth's past climate helped to understand the greenhouse effect [47]. It was found that the major drivers for the climate change in the pre-industrial period have been variations of the Sun, volcanic ashes, relative movements of the Earth towards the Sun, and tectonically induced effects. Shaped by orbital variations, responses such as the rise and fall of continental ice sheets and significant sea-level changes helped scientists to create the climate model. However, glacial variations may also influence climate without the orbital forcing.

The cycles of glaciations involve the growth and retreat of continental ice sheets in the Northern Hemisphere and involve fluctuations on a number of time scales, notably on the 23,000, 41,000 and 100,000 years cycles. Such cycles are usually interpreted as being driven by predictable changes in the Earth orbit known as Milanković's cycles, for Milutin Milanković, the famous Serbian astronomer and mathematician who is generally credited with calculating their magnitude. His cycles include three types of kinematic change: variations in Earth's orbital eccentricity (100,000 years), changes in the tilt angle of Earth's axis of rotation (41,000 years), and precession or wobble (23,000 years) [48]. Combined together, these cycles produce an impact on climate and are notable for their correlation to glacial and interglacial periods, as well as for the advance and retreat of the Sahara ([49]) and for their appearance in the stratigraphic records.

On time scales of millions of years, the uplift of mountain ranges and subsequent weathering processes of rocks and soils and the subduction of tectonic plates, are an important part of the carbon cycle. The weathering sequesters CO_2, by the reaction of minerals with chemicals (especially silicate weathering with CO_2) and thereby removing CO_2 from the atmosphere, thus reducing the radiative forcing. The opposite effect is volcanism responsible for the natural greenhouse effect by emitting CO_2 into the atmosphere, thus affecting glaciation cycles. A change in ocean circulation by the formation of Isthmus of Panama some 5 million years ago shut off direct mixing between the Atlantic and Pacific Oceans and strongly affected the ocean dynamics of what is now the Gulf Stream, and may have led to ice cover of the Northern Hemisphere [50].

The Earth's oceans contain a large amount of CO_2 in the form of bicarbonate and carbonate ions, much more than is the amount of CO_2 in the atmosphere. The bicarbonate is produced in reactions between rock, water, and CO_2. Such an example is the dissolution of calcium carbonate according to the following reaction: $CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca_2^+ + 2\ HCO_3^-$ [51]. Reactions between CO_2 and non-carbonate rocks also add bicarbonate to the seas. This natural process can later undergo the reverse reaction over millions of years to form carbonate rocks, releasing half of the bicarbonate as CO_2, thus disturbing its balance in the atmosphere and rising its temperature.

Ice sheet dynamics and continental positions have been important factors in the long term evolution of the Earth's climate. The presence or absence of land masses at the poles is not sufficient to guarantee glaciations or exclude polar ice caps [52]. The long-term evolution between hot and cold climates have been many short-term fluctuations in climate similar to, and sometimes more severe than, the varying glacial and interglacial states of the present ice age.

In their search for the best preserved evidence of the distant past, the scientists employ ice-coring in the ice caps to deduce ancient climates. The air found trapped within the fallen snow has proven a valuable source for direct measurement of the composition of air from the time the ice was formed. Layering as a result of seasonal pauses in ice accumulation was used to establish chronology, associating specific depths of the core with ranges of time [53]. Changes in the layering thickness of ice can be used to determine changes in precipitation or temperature. Pollen from the plants in the ice cores is used to understand which plants were present as the layer formed. Volcanic ash contained in some ice layers is used to establish the time of the layer's formation. The trees respond to changes in climatic variables by speeding up or slowing down growth, which is generally reflected by a greater or lesser thickness of tree-rings, dating back a few thousand years [53].

On a longer time scale, geologists refer to the sediments which contain remnants of preserved vegetation, animals, plankton, or pollen. Chemical signatures, particularly calcite, can be used to reconstruct past temperature. Coral 'rings' respond to water temperature, and can be used to derive the sea surface temperature and water salinity from the past few centuries, while the oldest remaining material is 200 million years old [54].

Rising sea levels due to the melting of the polar ice caps caused by global warming contribute to greater storm damage. To measure sea levels prior to instrumental measurements, scientists have used coral reefs that grow near the surface of the ocean, coastal sediments, marine terraces, and near-shore archaeological remains.

The Earth receives an influx of cosmic rays (ionized particles) originating from a variety of external sources, including the Sun. As an increase in the cosmic ray flux increases the ionization in the atmosphere, leading to greater cloud cover, this, in turn, would tend to cool the surface [16, 54].

Decreased ocean temperatures cause a decrease in CO_2 atmospheric concentration as, by Henry's Law (*the solubility of a gas in a liquid depends on temperature, the partial pressure of the gas over the liquid, the nature of the solvent and the nature of the gas*), CO_2 is more soluble in colder waters. For example, during the last glacial maximum, the decrease in the atmospheric CO_2 concentration due to temperature drop accounted for 30 ppm of the total decrease of 100 ppm [55].

Changes in the atmospheric composition

While the initial atmosphere would have consisted of hydrogen and other light gases, which could have escaped, partly driven off by the solar wind, the next atmosphere might have consisted largely of nitrogen and CO_2, produced by outgassing from volcanism and supplemented by gases produced by bombardment of Earth by huge asteroids. The CO_2 concentrations may have been high because there was no bacterial photosynthesis to reduce the gas to carbon compounds and oxygen. The constant rearrangement of continents by plate tectonics influences the long-term evolution of the atmosphere by transferring CO_2 to and from large continental carbonate stores.

The CH_4 may also have been more prevalent in the initial Earth atmosphere with a mixing ratio of 10^{-4} (100 ppm) [56]. After the lighter gases (*e.g.* hydrogen and helium), escaped to the space and oxygen was bound up in metals, the atmosphere is thought to have consisted mainly of CO_2, nitrogen, and inert gases from outgassing of volcanism. A major part of CO_2 emissions would have been dissolved in water and built up carbonate sediments, so that about 3.4 billion years ago, nitrogen would have been the major part of the atmosphere ([57]) as it is today. However, as the Sun emitted only 70% to 75% as much power as it does today ([58]), liquid water should not have existed on Earth if the atmospheric composition had been the same as today, and as there is evidence for the presence of water on the early Earth, scientists consider this fact as a paradox (known as the *faint young Sun paradox* [59]) and explain it by a much higher concentration of CO_2 than currently exist.

This is also in line with the early life forms dated to as early as 3.5 billion years ago [60], and the geological records which show a continually relatively warm Earth surface temperature with the exception of one cold glacial phase about 2.4 to 2.3 billion years ago [61]. This glaciation has been triggered by the evolution of oxygenic photosynthesis, which depleted the atmosphere of CO_2 and introduced free oxygen [62]. Free oxygen did not exist in the atmosphere until about 2.7 to 2.4 billion years ago (until the so called *great oxygenation event* [63]), when it began to develop from photosynthesizing cyanobacteria (until then, any oxygen produced by photosynthesis was consumed by oxidation of reduced materials, so that molecules of free oxygen did not start to accumulate in the atmosphere until the rate of production of oxygen began to exceed the availability of reducing materials). The amount of oxygen in the atmosphere has fluctuated over the last billion years, reaching a peak of 35% about 300 million years ago fig. 8 [64], until temporarily stabilization on 21%.

The changes in quantity of oxygen isotope ^{18}O and the ratio of ^{18}O to ^{16}O ($\delta^{18}O$) in ice layers represent changes in average ocean surface temperature (water molecules with heavier ^{18}O evaporate at a higher temperature than water molecules with normal oxygen isotope ^{16}O, so that $\delta^{18}O$ will be higher as the temperature increases [65]). Figure 9 shows variation of $\delta^{18}O$ over the past ~ 500 million years and a cycling of cold and hot periods, indicating those characterized by glaciations [66].

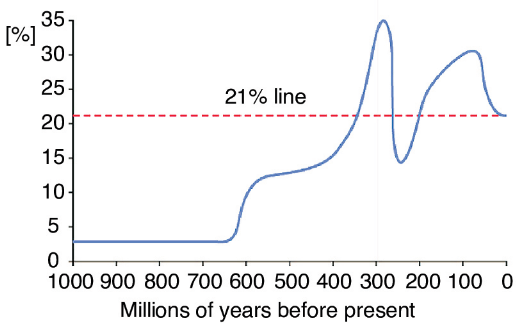

Figure 8. Atmospheric oxygen concentration [64]

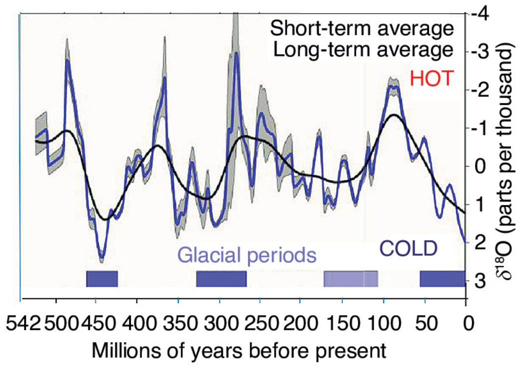

Figure 9. Climate change *vs.* $\delta^{18}O$ concentration [42]

The CO_2 concentration dropped from around 7,000 ppm about 500 million years ago through over 3,000 ppm between 200 and 150 million years ago ([67]) and about 760 ppm 34 million years ago (when Antarctic ice sheet started to take its current form) to less than 300 ppm by about 20 million years ago [30] to as low as 180 ppm during the last two million years [21], after a gradual intensification of an ice age 3 million years ago. During the last 800,000 years, atmospheric CO_2 concentration has varied between 180-210 ppm during the ice ages, and increasing to 280-300 ppm during warm interglacial periods, fig. 10 [68]. In relatively recent times, concentrations of CO_2 in the atmosphere were about 260 to 280 ppm and did not vary much from this level over the last 10,000 years [69].

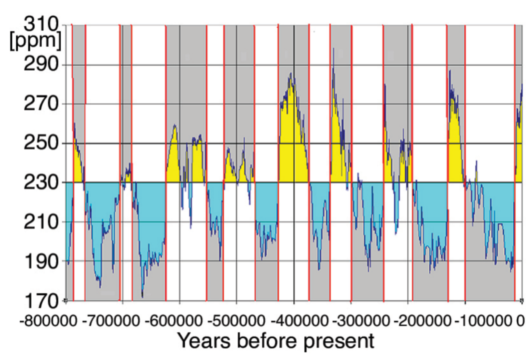

Figure 10. The CO_2 concentration over the last 800,000 years [68]

Glaciations on the Earth

Glaciers are considered to be among the most sensitive indicators of climate change. Their extent is determined by a mass balance between snow inputs and melt outputs. As the temperatures warm, the glaciers snow increases to make up for the additional melting.

The earlier history of Earth, when the continents were bunched up in the super-continent known as Rodinia, showed some major glaciations (*ice ages*). The first known glaciation in Earth's history lasted from 2.4 to 2.1 billion years ago [70], triggered by the first appearance of oxygen in the atmosphere. The next glaciation, encompassing the glacial maxima about 650 to 560 million years ago, has been proposed as a *snowball Earth* event with continuous sea ice reaching nearly to the equator [71]. One earlier glacial maximum around 730 million years ago may also have been a snowball Earth event, though this could not be proven yet [72]. The next (Andean-Saharan) glaciation lasted from 450 to 420 million years ago, and the Karoo glaciation from 360 to 260 million years ago, while the current (Quarternary) glaciation period began 2.58 million years ago [72].

In between these cold periods, warmer conditions were present and often referred to as *climate optima*. During the last 500 million years and almost the entire time since the origination of complex multi-cellular life on Earth, the temperature was fluctuating between ice ages. Roughly 4 such cycles have occurred during this time with an approximately 140 million year separation between climate optima, but it has been difficult to determine whether these warmer intervals were actually hotter or colder than occurred during the *climate optima* between 145.5 and 65.5 million years ago [7].

During the *snowball Earth* episode there have been negative excursions in the $^{13}C/^{12}C$ ratio, which is consistent with a deep freeze that could have killed off most or nearly all photosynthetic life [25]. The initiation of a *snowball Earth* event would involve some initial cooling mechanism (such as the eruption of a super-volcano, a reduction in the atmospheric concentration of GHG such as CH_4 and/or CO_2, changes in solar energy output, or perturbations of Earth's orbit [73]), which would result in an increase in Earth's coverage of snow and ice, and this would, in turn, increase Earth's albedo, which would result in positive feedback for cooling.

Global warming associated with large accumulations of CO_2 in the atmosphere over millions of years, emitted primarily by volcanic activity, is the proposed trigger for melting a snowball Earth. Due to positive feedback for melting, the eventual melting of the snow and ice covering most of Earth's surface would require a millennium. The CO_2 levels necessary to unfreeze Earth have been estimated as being 350 times what they are today (about 13% of the atmosphere [74]). Since the Earth was almost completely covered with ice, CO_2 could not be withdrawn from the atmosphere, and, enough CO_2 and methane (mainly emitted by volcanoes) would accumulate to finally cause enough greenhouse effect to make surface ice melt in the tropics until a band of permanently ice-free land and water developed (this would be darker than the ice, and thus absorb more energy from the Sun) initiating a positive feedback [74]. Because the *ice age* terminated only slightly before the rapid diversification of life, it has been proposed that this ice age (or at least its end) created conditions favorable to evolution.

Global temperature anomalies

Evidence for past temperatures from isotopic changes (especially $\delta^{18}O$) proved crucial in studies on glacial/interglacial temperatures [65]. Temperature reconstructions based on oxygen and silicon isotopes from rock samples have predicted much higher sea temperatures (these predictions suggest ocean temperatures of 55-85 °C during the period of 3.5 to 2.0 billion years ago, followed by cooling to more mild temperatures (between 10-40 °C) by one billion years ago [75]). Around 500 million years ago, life forms were abundant with average global temperatures of 22 °C ([76]) to 23 °C ([77]), 7 °C to 8 °C above the average global temperature today.

The length of glacial and interglacial cycles averages is approximately 100,000 years, as evident from the recent European Project for Ice Coring in Antarctica (EPICA) for the last 800,000 years. The thorough analysis of the EPICA core showed large temperature anomalies with eight glacial and interglacial cycles during that period, fig. 11. [68]. These are shown to correlate strongly with the variations of the atmospheric concentration of CO_2 during the same period, fig. 10.

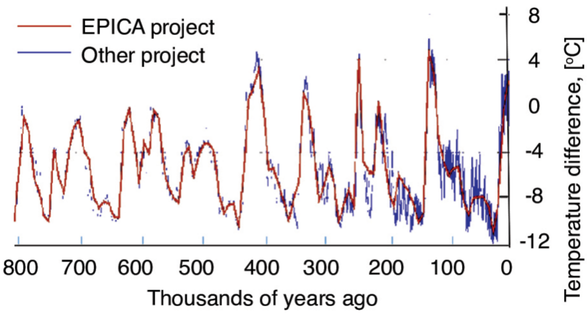

Figure 11. Temperature changes in the Antarctica [68]

A huge eruption of a giant super-volcano around 70,000-75,000 years ago reduced the global temperature by 5 °C and may have triggered an ice age, thus creating a bottleneck in human evolution [78]. Before the retreat of glaciers some 9,600 years BC the ice sheets covered much of the Northern latitudes, and sea levels were much lower than they are today. The periodicity of 100,000 to about 120,000-year long cycles, and asymmetry of the curves are believed to result from the interactions of many feedback mechanisms, but there is not yet enough scientific evidence to prove such a hypothesis [79]. The start of the present interglacial period appears to have helped spur the development of human civilization [80].

The most significant climate processes since approximately 3 million years ago are the glacial and interglacial cycles. An inverse correlation was found between dust flux and temperature records during glacial periods, but not during interglacial periods [81]. An increase in dust concentration over glacial periods is attributed both to strengthening of dust sources from volcanoes, and to a longer lifetime of dust particles in the atmosphere (troposphere) due to a reduced hydrological cycle that happens during the ice ages [82].

Figure 12 shows variations of CO_2 concentration, surface temperature and dust flux, reconstructed from the ice core for the past 420,000 years [3, 83]. While the temperature minima and maxima coincide with minima and maxima of the CO_2 concentration, it is the opposite case when considering the dust concentration because a rise of dust causes a decrease in the global temperature.

It has also been observed that the latest ice ages, related to the atmospheric concentration of CO_2, deepen by progressive steps, but the recovery to interglacial conditions occurs almost in one step, fig. 13 [84]. Figure 14 shows an upward temperature change since the last ice age ended about 11,700 years ago, compiled from ten various studies of evidence in different regions, with the thick black curve drawn as an average [85].

Scientists found that during the *greenhouse Earth* episode there were no continental glaciers on the planet, the levels of CO_2 and other GHG (such as water vapor and CH_4) were high, the sea surface temperatures range from 28 °C in the tropics to 0 °C in the polar regions [86]. Some 66 million years ago, large quantities of sulfate aerosols were released into the atmosphere, decreasing global temperatures by up to 26 °C and producing sub-freezing temperatures for a period of 3-16 years, so that the recovery time for this event took more than 30 years [87]. Five million years ago global temperatures were around 2 °C warmer than the present temperature, and, as a consequence, the sea level might have been much higher than today [88].

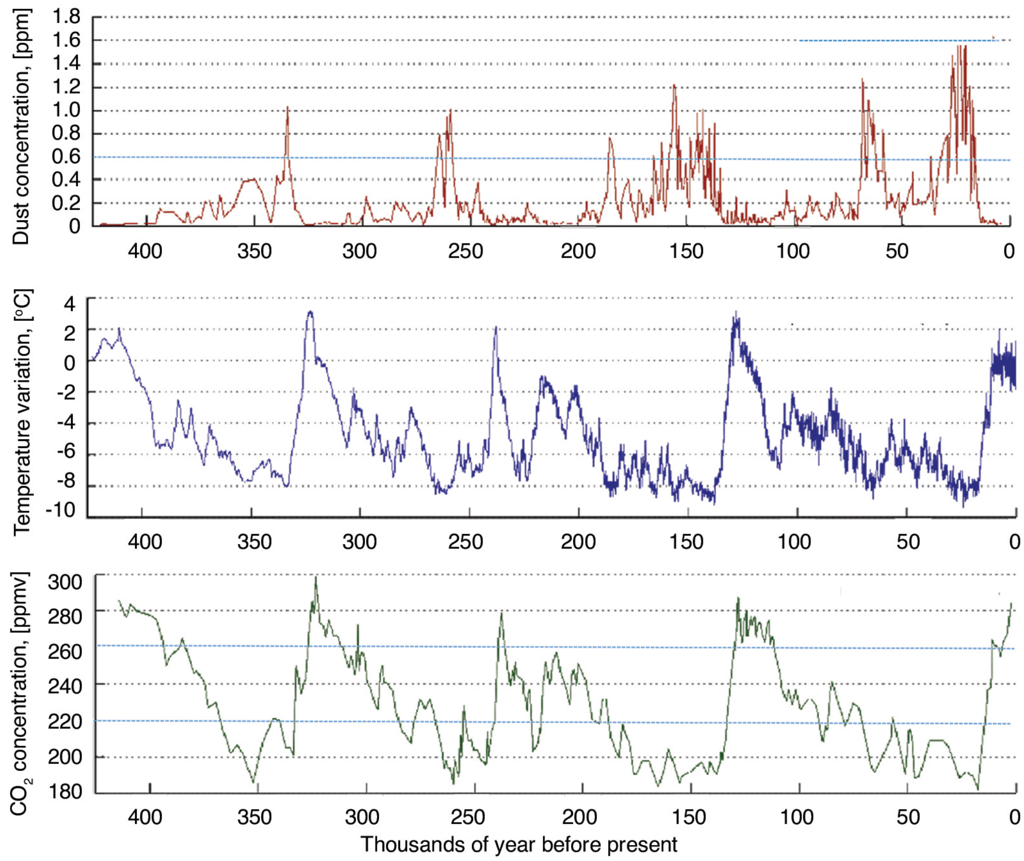

Figure 12. Variation of CO_2 concentration, average temperature, and dust fluxes [83]

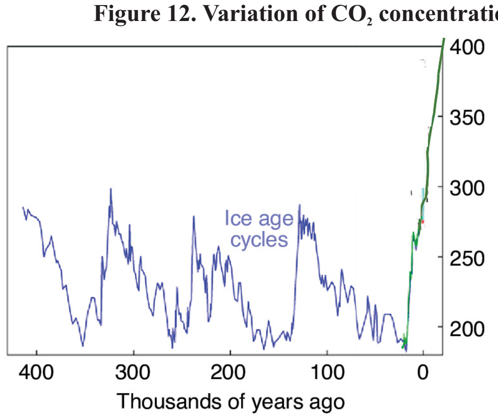

Figure 13. Variations of CO_2 concentration [84]

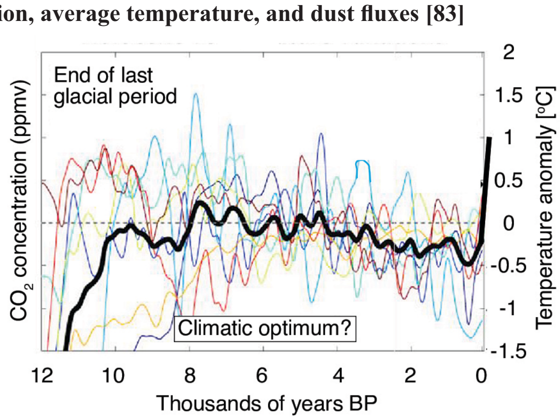

Figure 14. Temperatures since the last ice age [85]

Projected climate changes in the future

Challenges to address

On the long time scales, atmospheric CO_2 concentration is determined by the balance among geochemical processes including organic carbon burial in sediments, silicate rock weathering, and volcanism. The net effect of slight natural imbalances in the carbon cycle over tens to hundreds of millions of years has been to change atmospheric concentration of CO_2. On a time scale of billions of years, a downward trend appears bound to continue indefinitely as occasional massive releases of buried carbon due to volcanism will become less frequent (as Earth 'mantle' cooling and progressive exhaustion of internal radioactive heat proceeds further). The rates of these processes are extremely slow, and thus of no relevance to atmospheric CO_2 concentration over the next hundreds or thousands of years. This makes the role of human emissions of increasing relevance for future climate change.

In order to understand future climate projections, interactions of feedbacks and climate sensitivity with the background climate state has become a top priority in climate science. Excess CO_2 emitted since the pre-industrial era is projected to remain in the atmosphere for centuries to millennia [89]. Therefore, even if human CO_2 emissions were to cease completely, atmospheric temperatures are not expected to decrease significantly for centuries ([90]) or even thousands of years.

Scientists claim that their earlier projections of future climate changes are already happening. Increasing CO_2 in the atmosphere is being absorbed by the oceans, rising their acidification, damaging coral reefs and marine life. Areas that were once white with snow are now retreating to only the highest points of the world. Incidents of extreme weather are increasing, from flooding to tropical storms. Further ecological issues are the threat of extinction of different species and of major changes to the global landscape. Pressure is mounting on water and food sources, as eco-systems change and global populations continue to increase. The fact that the Earth's average temperature has gone up by about 0.8 °C over the past century and over 1 °C by now compared to pre-industrial temperature ([11]), might not seem like a lot for majority of decision-makers, but the climate system is so sensitive that the average temperature during the last Ice Age was only about 2.2 °C lower than it is today [91].

Climate model predictions

To explain why the climate has changed, and what the future climate is likely to be, scientists use analyses and predictions that rest on the results from computer models, but the science behind the calculations made by the climate models is not always easy to explain. Climate models are made out of theory with huge assemblies of equations that describe how sunlight warms the Earth, and how that absorbed energy influences the motion of winds and oceans, the formation and dissipation of clouds, the melting of ice sheets, and other things. These equations are all turned into computer code, linked to one another and loaded into a super-computer to calculate the time-evolution of the Earth system [92].

The conclusions drawn from a large number of model runs worldwide are that the Earth is rapidly warming, and that fossil-fuel burning is the principal driver of it. The calculations about how the future climate will be affected by the burning of fossil fuels are based on solid scientific theories that are well supported by the facts, but there still is a hesitation to act against major climate changes.

In response to global warming, sea level is expected to rise due to both, glacial retreat and thermal expansion of the water as the ocean warms. Because the deep ocean will warm more slowly than the upper ocean, the thermally driven rise in sea level is expected to continue for centuries after atmospheric CO_2 stops increasing. Figure 15 shows the estimated change in sea level caused by thermal expansion only, as calculated by the GDFL model [93]. This graph shows the projected change in the sea level rise if CO_2 concentrations were to either quadruple ($4 \times CO_2$) or double ($2 \times CO_2$). The sea level rise computed by the GFDL model is 1.75 meters for $4 \times CO_2$ after 500 years [93]. These sea level rise projections do not include the effect of melted continental ice sheets, so that, with the effect of ice sheets included, the total rise could be larger by a substantial factor.

A hypothetical forcing of 12-16 W m^{-2}, which would require CO_2 to increase by a factor of 8-16 times (if the forcing were due to CO_2 change only), could rise the global mean temperature to 16 °C-24 °C, with much larger polar warming, [94]. Such global warming is assumed to produce a sort of moderately moist climate, with water vapour increasing to about 1% of the atmosphere's mass, and an increase in the hydrogen 'escape rate' to the space [94].

If such forcing is by fossil fuel CO_2, the weathering process would remove the excess atmospheric CO_2 on a time scale of 10^4-10^5 years, well before the ocean is significantly depleted [95]. However, in the *hothouse* conditions, such a large long-term forcing is unlikely to occur until the Sun brightens by a few tens of per cent, which would take a few billion years [96]. In such hypothetical conditions, the Earth could become in large parts uninhabitable and may not even require burning all of fossil fuels, because of the much higher climate sensitivity and a variety of possible feedback mechanisms.

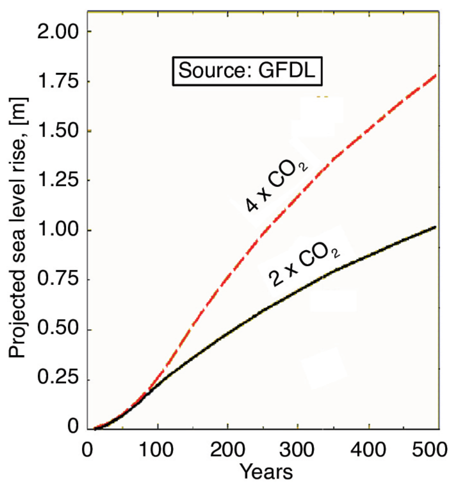

Figure 15. Sea level rise by thermal expansion [93]

There are different scenarios on how much the emissions of GHG would rise global temperature above the pre-industrial levels. Climate models predict that by the year 2100 the global temperature will rise by about 3-4 °C (based on a 550 ppm scenario [97]), or by 5.8 °C ([5]), or even as much as 6.1 °C [98]. This change would be much larger than any climate change experienced over at least the last 10,700 years, fig. 14. The projection is based on a wide range of assumptions about the main forces driving future emissions (such as population growth and technological change), but does not reflect current international efforts taken to control emissions and prevent climate change.

The International Energy Agency (IEA) in its publication on energy technology perspectives ([99]) presents three scenarios to demonstrate how the overall energy system would evolve from now to 2050 if the emissions either continue to rise at current rate, or be limited less and more strongly, resulting in temperature rise in the long term by 6 °C, 4 °C and 2°C respectively. More aggressive energy policies and technologies could lead to slower growth in CO_2 emissions than expected, but this would still not be enough to limit warming to no more than 2 °C pre-industrial levels [99]. That threshold has been recognized by governments as limiting the worst impacts of climate change, but the IEA has acknowledged that its 2 °C (*i.e.* 450 ppm GHG concentration) scenario, which would put the world on a lower-carbon trajectory, looks increasingly unlikely [99].

Model simulations suggest that the current interglacial climate state will continue for at least another 100,000 years, due to CO_2 emissions, including complete deglaciation of the Northern Hemisphere [100]. Scientists tried to compare the past transitions between *icehouse* and *greenhouse* states and vice versa to understand where the planet Earth is now heading. Without the human influence on the GHG concentration, the Earth would be heading toward a glacial period. Predicted changes in orbital forcing (Milanković's cycles) suggest that (in absence of human-made global warming) the next glacial period would begin at least 50,000 years from now [101]. But due to the anthropogenic GHG emissions, the Earth may, instead, heading toward a *greenhouse* Earth period [9].

In billion-year time scales, it is predicted that plant and animal life on the land will die off altogether, since by that time most of the remaining carbon in the atmosphere will be sequestered underground, and natural releases of CO_2 by radioactivity-driven tectonic activity will have continued to slow down [102]. The loss of plant life would also result in the eventual loss of oxygen [103]. Only some microbes are capable of photosynthesis at concentrations of CO_2 of a few ppms and so the last life forms probably would finally disappear due to the rising temperatures and loss of the atmosphere when the Sun becomes a *red giant* some four billion years from now [104].

Concluding remarks

A majority of scientific conclusions indicate that the Earth system is warming and that much of this warming is very likely due to human activities. The magnitude of climate change beyond the next few decades will depend primarily on the amount of GHG (especially CO_2) emitted globally. Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 6 °C or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature relative to the pre-industrial conditions could be limited to 2 °C. However, even if achieved, this goal will not be sufficient to make additional efforts by the humans to adapt to a warmer climate unnecessary.

Many climate-research groups around the world have calculated the various contributions to climate change, including those not related to humans, like orbital variations, volcanic ash and cosmic rays. It has been shown repeatedly that it is just not possible to explain the recent warming without factoring in the rise in anthropogenic GHG gases. The sophisticated climate models predict that, if nothing is done to reduce anthropogenic carbon emissions over the next couple of decades, there will be massive changes in the global precipitation and temperature patterns, with huge effects on water and food security, and possibly dramatic sea-level rise.

In despite of a consensus among nearly all scientists, scientific organizations, and governments that climate change is happening and that is caused mainly by human activity, a small number of them still questions the validity of such assertions and casts doubt on the preponderance of evidence. Climate change deniers claim that recent changes attributed to human activity can be seen as a small part of the natural variations in Earth's climate and temperature, and that it is difficult to establish a direct connection between climate change and any single weather event, such as a hurricane. While the latter is generally true, decades of data and analysis support the reality of climate change and the human factor in this process, as there is a strong, credible body of evidence, documenting that climate is changing and that these changes are in large part caused by human activities.

While much still remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of possible climate changes beyond repair. Scientists now have the tools to observe, understand, and predict climate change, and the humanity has the resources to reduce the chances of catastrophic warming. But, as the times goes on, there is either a hesitation or a very slow progress made in order to avoid such bad scenarios, insisting on many uncertainties still present in the climate model predictions.

Presented Paleoclimatology of Earth proofs that the model predictions are not a fiction, because such or even worse climate changes have been happening in the past and may not be neglected in the future due to an extreme sensibility of the climate system. This is why the international Paris climate agreement calls for limiting the rise of the global surface air temperature to 2°C or less above preindustrial levels to avoid climate change beyond repair. Economists agree that acting to reduce fossil fuel emissions would be far less expensive than dealing with the consequences of not doing so.

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