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Climate Change and carbon dioxide: geological perspective

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Abstract
The climate history of the Earth is a history of continuous change. Through geological time the average global temperature remained always within the constraints set by the presence of abundant liquid water, while the atmospheric CO_2 concentration varied strongly. Its 30% rise since the beginning of the 20th century can, at least partly, be attributed to human activities. According to the «general circulation models» (GCMs) used by the IPCC the ongoing rise in atmospheric CO_2 concentration will lead to significant global warming. However, in these GCMs the (small) net CO_2 forcing is amplified by strong positive feedbacks, particularly from water vapour and clouds. Real world observations and data of the geologic past do not support the role of CO_2 as the principal climate regulator.

1 Energy Budget

For geologists, the climate is just one of the subsystems of the System Earth. The climate is a manifestation of how solar shortwave radiation energy reaching the Earth is partly reflected back to space and partly absorbed by the oceans and continents, convectively redistributed by the atmosphere and hydrosphere, and re-radiated back to space as long-wave radiation. The climate is determined by a complex web of interacting processes, involving the incoming solar radiation, the atmosphere and its composition (such as the greenhouse-gases), the hydrosphere (including the oceans and the ice cover of the poles and high mountains), the biosphere, the topography (particularly mountain ranges), and dry land surface. The Sun provides the energy required for the operation of the climate system, including the average global temperature, all motions in the atmosphere and hydrosphere, and the continuous switch of water from its liquid and solid phase to its gaseous stage and back. Currently the solar energy received by the Earth amounts to about 240 W/m^2, but is not equally distributed over the globe, resulting in a wide range of temperatures and atmospheric pressures. Besides solar energy, there is also a minute contribution to the environmental heat budget of the Earth coming from its interior at an average heat flow of about 0.6 W/m^2. A major source of the internal energy is the decay of the radioactive isotopes of uranium, thorium and potassium in Earth's mantle and crust. Other sources include, among others, crystallization and zone refining of Earth's liquid outer metallic core, frictional heating of the Earth's mass exerted by the gravitational attraction of the Moon, the Sun and the other planets, and perhaps some gravitational heat remaining from the accretion of our planet. The internal heat production is the main driving force of all (plate)-tectonic and magmatic (volcanic) processes. However, the total energy budget of the Earth has changed considerably since the birth of the Solar System 4.57 billion years ago. According to the standard model of stellar evolution, solar radiation

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has linearly increased by about 25% since then, whereas the Earth's internal radiogenic heat production has decreased to about 20% of its initial value. Solar radiation will continue to increase, while the Earth will continue to cool.

2 Climate

The geologic record shows that the climate system is in constant motion and changes continuously (Fig. 1). The oldest known sediments were laid down 3.8 billion years ago in marine environments and the oldest evaporates date from about 3.5 billion years ago, evidencing that the Early-Archaean Earth had already substantial amounts of liquid water and at least a modest atmosphere (liquid water would evaporate completely at an atmospheric pressure below 6 mbar). Sedimentological studies suggest that water depths were up to a few kilometres, indicating the presence of substantial oceans [1]. Except for the first 5% of our planet's existence (for this period there is no geological record), the sedimentary record shows that liquid water was always present.

The System Earth has thus managed to maintain over the last 3.8 billion years, at least at lower latitudes, surface temperatures within the rather narrow range in which liquid water can exist, despite the steadily increasing heat output of the Sun. This distinguishes the Earth from the other terrestrial planets of our Solar System. Some kind of a global climate regulation system must always have been operating, a natural planet-sized thermostat, preventing the planet from freezing early in her history and counteracting the tendency of the surface temperature to rise with the steadily increasing solar radiation. However, it is estimated that approximately one billion years in the future the increasing heat input from the Sun will overwhelm the capacity of «Earth's thermostat». The oceans will then evaporate, while the internal heat production will gradually come to an end. Our planet will ultimately become a hot, dry and geologically dead rock body that, like many others in the Universe, will no longer be capable to sustain life.

3.5 Billion years ago the luminosity of the Sun was about 20% lower than today [2]. Consequently, the Earth received less solar energy and calculations indicate that the effective surface temperature should have been about 10-15 °C lower than today. However, the Earth's surface temperature was in fact quite similar to that of today.

This is known as the Faint Young Sun Paradox [3]. This paradox is usually resolved by

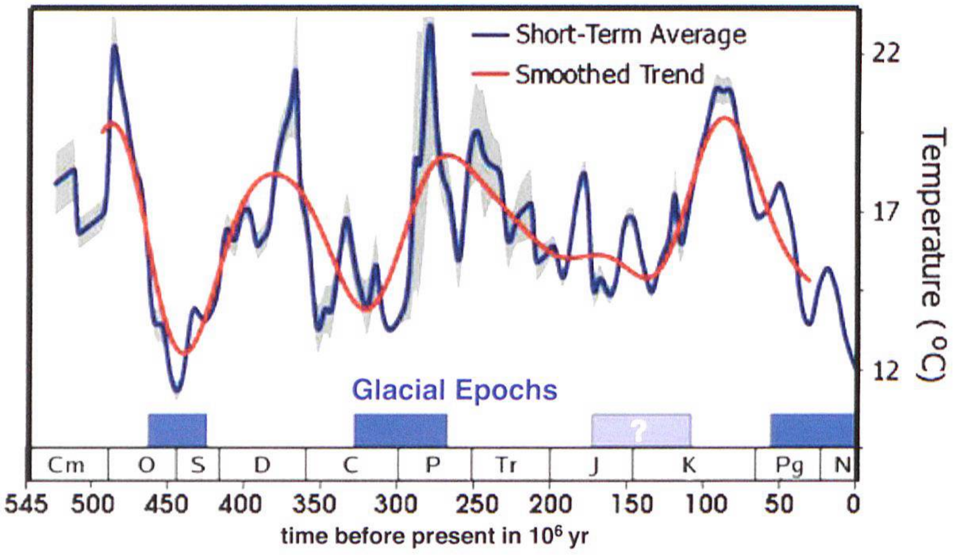

Fig. 1: Long-term variation in the global temperature over the last 540 Ma based on the oxygen isotope ratios $^{16}O/^{18}O$ in calcitic shells [66]. For the Jurassic/Cretaceous glacial epoch no true polar ice caps have been documented.

assuming that the young Earth's atmosphere, that in the very beginning was formed by the emission of volatiles from the (partially) molten mantle, initially consisted of N_2, H_2O vapour and about 25% CO_2 [4] and thus had a substantially stronger greenhouse effect than today. However, if true, this high initial partial CO_2 pressure was rapidly lowered by processes such as silicate weathering [5], so that by Late Archaean time (2.75 billion years ago) the CO_2 level had decreased to about 9,000 ppm, much less than required to defeat the faint Sun [4]. This is reflected by, among other things, the occurrence of minerals such as hematite (Fe_2O_3) and greenalite (a complex hydrous ferric-ferrous iron silicate) in Late Archaean-Early Proterozoic weathering surfaces (paleosols). The formation of these minerals is not consistent with weathering under a high CO_2 pressure - the stable iron compound is then siderite ($FeCO_3$).

A solution for the Faint Young Sun Paradox may have to be sought in the surface conditions and environmental energy budget of the young Earth, which must have differed considerably from those of today. For example, for the first one and a half billion years or so the Earth was an «oceanic planet», with oceans covering most of its basaltic crust and only very little dry land. This situation lasted until about 3.5 billion years ago, when massive volumes of dioritic material began to segregate from the Earth's basaltic crust, gradually transforming the «oceanic Earth» into the modern planet with continents (on average of dioritic composition) making upabout 35% of its crust [6]. Due to the low albedo of the ocean surface, which reflects only 2% of the solar radiation, the «oceanic» Earth must have absorbed a much greater portion of the incoming solar energy than today. Moreover, the radiogenic heat production of the ancient Earth was considerably higher, while much heat was still available from the Earth's accretionary stage. This accounted for a high heat flow and intense volcanic activity emitting enormous quantities of water vapour (the strongest greenhouse gas) and carbon dioxide, thus warming the planet [1]. With the passage of time the Earth cooled down, in the beginning rapidly and then more slowly, while solar irradiation steadily increased and the evolving biosphere became a major factor in regulating the surface temperature.

3 Carbon Dioxide

Around 2 billion years ago the biosphere had developed to the point at which photosynthesis played an important role and molecular oxygen began to accumulate in the atmosphere at the expense of CO_2, as evidenced by the disappearance of easily oxidized minerals such as uraninite (UO_2) and pyrite (FeS) in placer deposits and the first occurrence of red beds (sediments made of mineral particles coated with hematite, Fe_2O_3, that formed as the result of subaerial oxidation). Atmospheric oxygen began, however, only to build up rapidly with the development of higher organisms around 750 million years ago, reaching at times considerably higher values than at present. Ever since, the atmospheric CO_2 concentration varied continuously and it was much higher than the present value of 394 ppm (Fig. 2) over most of antiquity. Throughout the Phanerozoic (i.e. the last 540 million years) the exchange of CO_2 between the oceans and the atmosphere was closely balanced, with the atmospheric CO_2 concentrations fluctuating between roughly 7,500 and 200 ppm [7]. Only during the Late Carboniferous-Early Permian and the Late Tertiary did atmospheric CO_2 concentrations decrease to the very low levels of today. However, all the carbon contained in sediments, atmosphere, oceans and the biosphere is only a tiny fraction of the Earth's carbon content, most of which is hosted by the mantle.

Degassing of juvenile (mantle-derived) CO_2 from the mantle is a continuous process. It is released by volcanism associated with diverging plate boundaries, such as the world-encircling system of seafloor spreading axes where basaltic magma derived from the mantle well up to the seafloor at rates depending on the seafloor spreading rates. Large volumes of juvenile CO_2 are also exhaled by volcanoes related to mantle-plumes, stationary diapirs of hot material rising up from the deep mantle. Volcanoes associated with convergent plate boundaries exhale CO_2 that is partly juvenile and partly «recycled», stemming from subducted sediments.

The concentration of CO_2 in the atmosphere is determined by a global system of supply and extraction. CO_2 is continuously added to the atmosphere by degassing of the mantle and from crustal melting, as well as by «exchangeable reservoirs» such as the biosphere and the oceans, and since industrial times by the consumption of fossil fuels. This input is offset by the continuous withdrawal of CO_2 from the atmosphere by the oceans and by biological, chemical and geological processes (Fig. 3). This whole «biological-geological control system» tends to adjust itself until the rates of input and output are equal when averaged over the residence times of CO_2 in the exchangeable reservoirs. Particularly the inputs and outputs to and from the atmosphere/ocean reservoir tend to be closely balanced [7], with geologically speaking very short residence times [8], while limestone and dolomite formations and fossil biomass reflect long-term CO_2 storage.

Volatiles exhaled by volcanoes consist for about 80% of water vapour, 20% of CO_2 and other carbon compounds (in the atmosphere oxidized to CO_2), and minor amounts of a wide variety of other compounds. The water emanated along with CO_2 by volcanism and from exchangeable reservoirs condenses at the saturation point and is added to the hydrosphere, while most of the exhaled CO_2 accumulates in the atmosphere, were it not continuously removed by «natural pumps». Two of these pumps, the «carbonation pump» (chemical weathering of rocks enhanced by bacterial activity) and the «carbonate pump» (biological precipitation of carbonate in oceans) lead eventually to the sequestering of large volumes of CO_2 in enormous sedimentary sequences, including limestones and dolomites. The third, the «biomass pump» (photosynthesis,

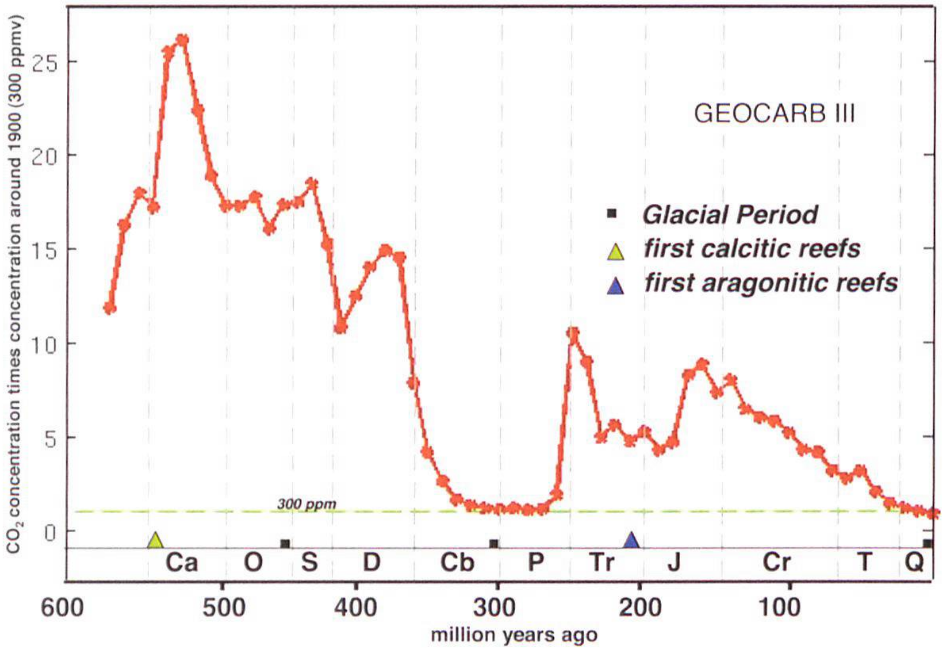

Fig. 2: Long-term variation in the level of atmospheric CO_2 over the last 540 Ma. Process-based model, 10 million year time-steps [67].

followed by burial of organic matter), sequesters CO_2 in soils, peat, coal, organic-rich shales, hydrocarbon source rocks, carbonates and as dispersed carbon compounds in sediments. If all carbon that is stored in sediments and meta-sediments and that is dissolved in the oceans would be released into the atmosphere, the surface CO_2 pressure would be at least 70 bar, that is 200,000 times the present value. Our atmosphere would then resemble that of Venus (apart from the absence of water on Venus). Both planets possess a similar amount of free CO_2, but whereas on Venus the free CO_2 resides as the principal constituent of the atmosphere, on Earth the vast majority is stored in sediments and in the oceans.

Carbon dioxide is a natural greenhouse gas in the atmosphere, along with water vapour and some trace gases. It is a physical fact that greenhouse gas molecules absorb thermal infrared radiation emitted by Earth's surface and remit it radially, thus partly back to the Earth, keeping the surface air warmer than it would be otherwise. This is referred to as the greenhouse effect. The degree to which CO_2 and water vapour are responsible for warming of the lower atmosphere is a key subject of the current climate controversy. It is generally agreed that water vapour and CO_2 together are responsible for nearly the entire greenhouse warming and that the effect of water is far stronger than that of CO_2. The specific contributions to the total greenhouse warming are disputed,with 36% to 90% being quoted for water vapour and clouds, and 4.2% to 26% for CO_2. It should be noted that the total natural greenhouse warming must be less than the generally accepted 33 °C. This number was obtained by applying the Stefan-Boltzmann law, assuming that the Earth is a flat black body without an atmosphere and oceans that reflects 30% of the incoming solar radiation as infrared radiation [9]. However, as our planet is not such a black body but a globe with oceans, atmosphere and biosphere, its natural greenhouse warming must be lower.

Air bubbles in ice cores from Antarctica and

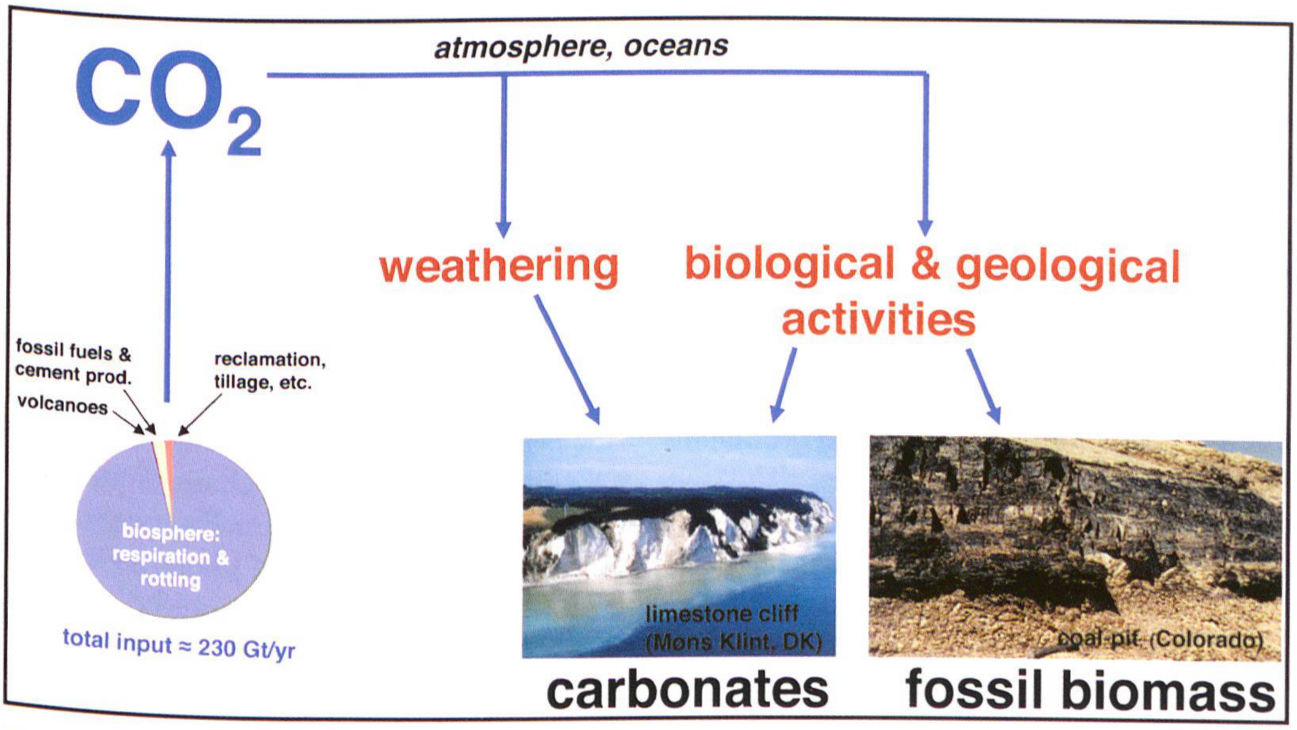

Fig. 3: Sources and Sinks of CO_2 in Earth's environment (the input by volcanoes includes juvenile carbon from the mantle). The oceans and atmosphere are «exchangeable reservoirs», with the oceans containing about 60 times more CO_2 than the atmosphere. The ocean-atmosphere system tends to adjust itself until the rate of CO_2 output equals that of the input.

Greenland show for the last millennia no significant variation in CO_2 concentrations. They always hover around the pre- industrial level of around 280 ppm. On the other hand, leaf-stomata from peat and lake sediments in The Netherlands record for the first half of the last millennium atmospheric multidecadal CO_2 fluctuations of up to 34 ppm [10]. The nearly constant concentration in air bubbles of ice cores is probably due to the smoothing effect of diffusion processes in firn layers. Since the beginning of the industrial era in the late 19th century the atmospheric CO_2 concentration has steadily increased to the present level of 394 ppm and continues to increase at an average rate of about 2 ppm per year. The gradual change in the carbon isotope ratio of atmospheric CO_2 during industrial times is generally interpreted as indicating that the rise in CO_2 concentration is for a substantial part or entirely due to anthropogenic emission [9, 11]. Since the beginning of the 20th century about 620 gigaton of CO_2 has been added to the atmosphere. However, the cumulative release of CO_2 from fossil fuel burning, cement manufacturing and oxidation of organic matter exposed by soil tilling and deforestation is estimated at about 1200 gigaton. Natural processes have thus already taken care of half of the anthropogenic CO_2 emissions through uptake by oceans, living organisms (mostly forests of boreal and temperate zones, and oceanic plankton), weathering processes, and unidentified sinks. This reflects the rapid response of the biological-geological control system to rising atmospheric CO_2 concentrations. In this context it is noteworthy that about one fifth of the atmospheric CO_2, corresponding to about 600 gigaton, is annually exchanged with natural sinks, while anthropogenic emissions amount to 32.5 gigaton. Moreover, carbon isotope mass balance calculations suggest less than 10% originates from anthropogenic emissions [12].

There is a widespread fear that rising atmospheric CO_2 concentrations may lead to acidification of the oceans. From a geochemical point of view this is, however, unlikely. Presently the pH of ocean water ranges between 7.5 and 8.2 [9]. The IPCC claims that the pH of the oceans has decreased since pre-industrial time by about 0.1 unit. It predicts that the pH will decrease by 0.14 to 0.35 units towards the end of the 21st century and, if this trend should continue in the future, this will have serious consequences for marine life, particularly corals. The oceans are, however, not filled with distilled water, but contain several buffers that counteract acidification, such as the carbon dioxide/carbonic acid/bicarbonate equilibrium and marine silicate equilibria (clay minerals and the basaltic floor of the oceans [13]). Interestingly, much higher atmospheric CO_2 concentrations than the currently prevailing ones did not impede in the Lower Cambrian (about 530 million years ago) the development of the first carbonate constructions built by the calcite skeletons of stromatolites (calcareous algae) and archaeocyathids (extinct group of calcareous cup-shaped spongelike organisms), nor in the Late Triassic (about 210 million years ago) the first development of coral reefs consisting of aragonite (upon burial converting to calcite) (Fig. 2).

4 Climate Change

The climate history of the Earth is a history of continuous change and not of stability. Under the constraints given by the continuous presence of liquid water, the Earth's surface temperature always changes at different time-scales, both regionally and globally. Abrupt short-term global climate changes can be related to processes such as ocean current oscillations and volcanic eruptions. Particularly oscillations of ocean currents cause global short-term climate changes, such as the notorious El Niño/La Niña-Southern Oscillation (ENSO) in the eastern tropic Pacific Ocean. The ENSO phenomenon refers to variations in the temperature of surface water (warming and cooling known as El Niño and La Niña, respectively) and in the air surface pressure in the eastern Pacific. The two variations are coupled: the warm phase (El Niño) and the cold phase (La Niña) accompany high and low air surface pressures in the western Pacific, respectively, but the driving mechanism(s) of the ENSO is not yet well understood. The El Niño and La Niña events last for 9 months to 2 years and occur at intervals of 3–7 years, in extreme cases causing world-wide heat-waves, severe winters, floods and droughts. The ENSO events are superimposed on the Pacific Decadal Oscillation (PDO) that is characterized by two different oceanic and atmospheric circulation patterns. These alternate with each other every 20–30 years with a cyclicity of about 60 years and control changes in areas of warm and cold Pacific surface waters. Global surface temperatures of the last 150 years clearly reflect the positive (warming) and negative (cooling) phases of the PDO during which EL Niño, respectively La Niña phenomena are more frequent [14, 15, 16]. The driving mechanisms of the PDO and ENSO are attributed to lunar and soli-lunar tidal forces and variations in solar irradiance [16, 17].

Volcanic eruptions can impact on the global climate by emissions of ash and SO_2 gas (converted in the air to micro-drops of sulphuric acid) that form nuclei for cloud formation, thus screening the Earth from solar irradiation and increasing its albedo. Although the 20th century was characterized by overall low volcanic activity, historical records show that abrupt cooling phases lasting for several years can follow major explosive eruptions. This occurred, for example, after the catastrophic explosion of the Tambora on the island Sumbawa (Indonesia) in 1815, that was followed by 0.4–1 °C global cooling for more than two years, leading locally to disastrous crop failures and famine. The year 1816 is world-wide known as the «year without a summer». The Tambora volcano is located along a converging plate boundary, similar to the volcano that formed with a much bigger explosion 72,500 years ago the Toba caldera complex on Sumatra (Indonesia) and is thought to be responsible for a population bottleneck that affected the genetic inheritance of all humans today [18]. Explosions of gigantic magnitude such as those of Toba and the intraplate supervolcano Yellowstone (USA), the latest giant eruption of which occurred 640,000 years ago (there are several younger, smaller eruptions), caused prolonged global cooling periods and could certainly do that again. However, during the last 540 million years, the Phanerozoic, volcanic eruptions associated with convergent plates did on the whole not play a significant role in the global climate system. By contrast, intraplate volcanic activity related to mantle-plumes (stationary diapirs of hot material rising from the deep mantle) that impinge on the continental lithosphere can give rise to the outpouring of enormous volumes of flood basalts during millions of years, covering vast areas and causing severe detoriation of global marine and terrestrial environments. Some of them caused world-wide rapid evolutionary changes in the biosphere, recognized by the sudden disappearance of large groups of organisms from the fossil record (mass extinctions or punctuated equilibria). Examples are the development of the Late Permian Siberian Flood Basalt Province (around 252 million years ago), the Late Triassic Central Atlantic Magmatic Province (around 202 million years ago), and the Late Cretaceous Deccan Traps of India (around 65.5 million years ago). All three events were associated with important biotic mass extinction events [19, 20, 21, 22, 23].

Superimposed on rapid short-term climate fluctuations (partly with unknown causal relation) there are decades and centuries of globally warmer or cooler climatic conditions. During the last two millennia, the Roman Warm Period came to an end around 400 AD and gave way to the cold Dark Age

Period of 500 to 850, a period of massive migrations in Europe and central Asia. The subsequent Medieval Warm Period of 900 to 1350 lured Norsemen to colonize Greenland and explore the North American east coast. The settlements on Greenland were abandoned when pack ice advanced southward at the onset of the Little Ice Age that lasted from 1550 to 1850, a period of cold winters, crop failures and political unrest in Europe. The beginning of the Modern Warm Period heralded the industrial revolution of the 20th century and the massive proliferation of the human population. These important climatic oscillations were not restricted to Europe, but are global phenomena. Paleoecological data document for the last 10,000 years a continuous succession of warm and cold periods lasting for centuries and millennia [24, 25]. Worth mentioning is that the largest global climatic shift in the last 10,000 years occurred around 4000 BC, when the global temperature rose by 2–3 °C and the Sahara transformed within a few centuries from a savannah with grasslands and low bushes to the desert we are familiar with today, causing the disappearance of several ancient civilisations [26]. Sometimes the transition from one climate to another occurred very rapidly, occasionally in as little as a decade or less [27]. For example, the Younger Dryas cold spell in the Northern Hemisphere began abruptly 12,900 years ago and came to an equally abrupt end 11,500 years ago [28]. Several possible geological and astronomical have been invoked to explain these abrupt climatic changes. The most dramatic instance of abrupt global warming occurred about 56 million years ago at the onset of the so-called Paleocene/Eocene Thermal Maximum (PETM), when mean annual surface temperatures increased by 5–8 °C, precipitation and vegetation patterns changed worldwide dramatically, and atmospheric CO_2 concentrations increased to about 1200 ppm [29]. The cause(s) of this transient climate perturbation is likewise subject to ongoing debate.

It is a long-held suspicion that there is a causal relationship between solar activity and the Earth's surface temperature. Support for this notion comes, for example, from historical records reporting that the coldest years of the Little Ice Age, between 1650 and 1710, coincided with a prolonged period during which sunspots were conspicuously absent. The sunspot number, as well as transient solar flares, are readily visible manifestations of changes in solar activity. More complex observations on parameters such as the Total Solar Irradiance (TSI), the solar spectral irradiance (SSI), the solar radio emission and UV irradiance, and the open solar and galactic cosmic ray flux also document variations in solar activity, which are, however, very small in terms of the total energy output of the Sun [30]. This applies particularly to the TSI (luminosity), which, despite varying apparently by only a few tenths of percent, plays a dominant role in modulating the global climate [31, 32, 33, 34, 35]. However, although there is disagreement about the magnitude of TSI fluctuations [36], they appear to account for only about 40% of the post-Little Ice Age warming [35, 37]. This suggests that TSI-dependent direct solar forcing is amplified by indirect solar forcing mechanisms which are not related to TSI [17].

Svensmark and Friiss-Christensen [38, 39] proposed that the Galactic Cosmic Ray (GCR) flux provides such a potential indirect solar climate forcing mechanism. This paradigm is based on (a) the fact that the solar interplanetary magnetic field, the solar wind and the geomagnetic field, which together shield the Earth from the GCR flux, are more intense during periods of high solar activity than during periods of low solar activity, and (b) the fact that cosmic rays ionize volatile compounds in the atmosphere, leading to clustering of molecules (aerosols) that act as condensation nuclei for cloud formation. Correspondingly, a lower cosmic ray flux is thought to bring about via a lower aerosol production, a lower cloudiness, leading to a higher global temperature, and vice versa. This paradigm is compatible with the observed correlation between cloud cover and the GCR flux during the years 1984 to 2005 [40]. It is also supported by the variations in the abundance of the cosmogenic isotopes ^{14}C and ^{10}Be in tree rings and ice cores, respectively, which provides a record of solar activity through time [41, 42] and is inversely proportional to the ambient temperature under which trees grew and snow was precipitated [32,43]. More support for the causal relationship between the GCR flux and nucleation processes in the atmosphere is provided by experiments under controlled conditions [44, 45, 46], particularly in the CERN/CLOUD ionization chamber [47].

During Late Precambrian and Phanerozoic times, five or six episodes are recognized during which grounded ice sheets covered large parts of the Earth's surface for tens of millions of years. These glacial epochs, usually referred to as Ice Ages, were separated by very long periods during which there is no evidence for an extensive year-round ice cover (Fig. 1). This is the most persuasive evidence for global climatic change in the Earth's history. Development of glacial epochs was accompanied by a long-term decline of global surface temperatures and probably increasing precipitation. Changes in the distribution of the continents and their drift into polar areas in response to plate-tectonics, and consequent changes in ocean currents and atmospheric circulation patterns have probably played an important role. Some astronomers speculate that the development of the ice ages can be related to the passage of the Solar System through spiral arms of the Milky Way Galaxy on its orbital path around the centre of the galaxy (revolution period 224 million years, the «galactic year»). When the Earth crosses through a galactic spiral arm it may be exposed to an increased GCR flux, plausibly up to a factor 3, that could lead to increased cloud cover, global cooling and higher precipitation [48 ,49, 50]. The Solar System's motions about the galaxy may possibly be linked to a quasi-periodicity of the order of about 140 million years in global cooling [49]. The Solar System does not operate in splendid isolation!

Particularly the Late-Precambrian glacial period between about 720 and 660 million years ago was extreme, with polar ice sheets advancing to about 30° latitudes. It is, however, uncertain whether this was one discrete ice age which lasted for about 60 million years, or whether it consisted of multiple glacial episodes. We are living in the glacial epoch that began around 40 million years ago with the first development of ice sheets on the Antarctic continent that had drifted into a polar position during the Late Cretaceous. In the earliest Oligocene (33.6 million years ago) these ice flows reached the coast, as evidenced by ice-rafted detritus in deep-sea cores, and became the driver of the Antarctic circulation, which in turn affected global climate [51]. In the Arctic region the glaciation of Greenland began in the Late Miocene (10^{-6} million years ago), but gained momentum in the Middle Pliocene (about 3 million years ago) [52]. Ice cores and sedimentary sequences reveal for the last 1.8 million years a cyclical succession of advances and retreats of the ice sheets, the glacial and interglacial stages that are characterized by temperature fluctuations of 5-6 °C. This cyclicity is attributed to solar irradiation fluctuations in response to variations in the Earth's orbit around the Sun. This co-called Milankovitch cyclicity has also set its mark on fine-layered sedimentary successions deposited throughout geologic history. Superimposed on these orbital changes in solar irradiation there are variations in solar activity, which are attributed to tidal forces exerted on the Sun by its planets [36, 53, 54, 55]. The human species evolved during the current glacial epoch and all civilisations developed during the present interglacial stage that began about 11,500 years ago. The Milankovitch cyclicity predicts that Earth will in time undergo a gradual cooling and renewed extensive glaciation, with severe repercussions for humanity.

5 Carbon Dioxide Forcing of the Climate System

A rising concentration of atmospheric CO_2 (and other greenhouse gases) leads to an increased infrared absorption capacity of the troposphere, enhancing the greenhouse effect. However, the greenhouse effect by CO_2 decreases logarithmically with increasing concentration. According to Arrhenius' simplified first-order approximation for carbon dioxide forcing (without feedbacks), even a doubling of the pre-industrial atmospheric CO_2 level would lead to a global temperature rise of at most about 1.1 °C. The General Circulation Models (GCMs) used by the IPCC assume that in case of a doubling of atmospheric CO_2 concentrations from the pre-industrial level of 280 ppm, the net radiative CO_2 forcing is strongly amplified by positive feedbacks of about 2.1 °C, mainly by the interaction with water vapour and clouds, leading to a net warming of about 3.2 °C (2.0–4.5 °C). These GCMs overestimate, however, the CO_2 forcing effect by erroneously assuming a strongly positive feedback from water vapour, clouds and albedo. For example, on the basis of observational evidence it has been calculated that the combined feedback by water vapour, clouds and albedo (largely concentrated in the tropics) is actually negative for a doubling of CO_2, reducing the net warming of CO_2 doubling to 0.7 °C (0.5-1.3 °C at 99% confidence level) [56].

The GCMs are sets of mathematical equations that attempt to describe climate controlling processes and forecast climates under a range of CO_2 emission scenarios. The basic physics underlying these models do make sense, but the computer-generated projections depend entirely on input parameters and algorithms that appear to have only limited or no connection to the real climate. As not all climate-controlling factors can be adequately quantified nor are fully known, GCM-based projections create, in fact, a virtual reality. Those who claim that the response of the real climate to radiative forcing is adequately represented by the GCMs used by the IPCC have the obligation to prove that they have not neglected non-linear, possibly chaotic forcing and/or feedback mechanisms that Nature itself employs. Contrary to the short-term weather predictions, for which the climate models can be developed and corrected by trial and error, the long-term GCMs cannot be tuned any faster than climate evolves. So far, they even fail to adequately reconstruct climate developments during the Modern Warm Period, such as the cooling of 1940–1975 and since 1998.

The GCMs have shown to be inadequate in reproducing past climates when tested against the developments of recent and past global climates [36]. This is even more so when going further back in geologic time, due to increasingly different environmental conditions, and particularly when CO_2 is considered as the primary climate driving factor. For example, during the Mid Cretaceous, 100–120 million years ago, the average global temperatures were 6–10 °C higher than today and the atmospheric CO_2 levels were between two and eight times higher than the pre-industrial level of 280 ppm [57]. This high CO_2 level may be related the high rates of sea-floor spreading and pulses of plume-related volcanic activity [58], such as the outflow of the enormous volumes (some 100 million km^3) of basaltic lava forming the Ontong-Java, Manihiki and Hikurangi Plateaus in the Southwest Pacific Ocean, the largest volcanic event on Earth during the last 300 million years. Moreover, the land surfaces had little relief, the sea level was higher, and the dry land area much smaller than today. Due to the scarcity of high mountain ranges the heat transfer from the tropics to the poles was not impeded and a flat latitudinal temperature gradient prevailed. The tropics were about 7 °C cooler than today, while Polar regions were about 13 °C cooler than the tropics. Apart from Mid Cretaceous ice-rafted drop-stones in marine sediments at high latitudes, apparently derived from alpine-type glaciers on mountains [59], there is no evidence for any glaciation. When tested against the Mid Cretaceous Earth, the greenhouse scenarios of the GCMs underestimate the polar warmth and overestimate the tropical temperature relative to the reconstructed real data, implicating that other climate-controlling factors must have played a leading role. Further back in time, in the Late Ordovician (440–450 million years ago), the atmospheric CO_2 concentration was about 17 times higher than today (Fig. 2). Still, the tropics were not abnormally warm, while a large ice cap covered the polar part of Gondwana [60].

The fundamental assumption that atmospheric CO_2 concentrations are the main driver of global temperatures, is not compatible with the Mid Cretaceous and Late Ordovician climates, nor is it borne out when tested against more recent data. During the Middle Pliocene (3.3-3.0 million years ago) the global average surface temperatures were about 2-3 °C higher than in our time [61], but the atmospheric CO_2 concentration was only about 400 ppm, the same as today [62]. According to the GCMs such high temperatures would require a twice as high CO_2 concentration, however, which casts doubt on the widely held notion that this warm period may represent an analogue of the future climate. The Middle Pliocene warm period came to an end with the closure of the Panama seaway between the Pacific and Atlantic Ocean, that had an enormous impact on the Earth's climate. The newly-formed Panama Isthmus re-routed ocean currents in both the Atlantic and Pacific Oceans. Atlantic currents were forced northward, and eventually settled into the present current pattern with the Gulf Stream transporting warm Carribean waters to the Northeast Atlantic. The climate of northern Europe grew warmer, with winters being as much as 10 °C warmer than they would be without the warming effect of the Gulf Stream. Moreover, the closure of the Panama Isthmus and development of a warmer North Atlantic climate was apparently accompanied by the expansion of the Greenland ice cap, maybe in response to increased precipitation, and contributed to the current glacial epoch at high latitudes in the northern hemisphere that cannot be reconciled with the GCMs. Similarly, temperatures during the Medieval Warm Period were at least as high as today, but leaf-stomata indicate that CO_2 concentrations never rose above 315 ppm [10], much below the present level of 394 ppm that, according to the GCMs, is responsible for current temperatures.

Antarctic ice core data show for the last 450,000 years that during glacial stages the atmospheric CO_2 concentrations and temperatures were about 100 ppm and 5-6 °C lower than during interglacial stages, but that CO_2 changes lag behind temperature changes by up to hundreds of years. Similarly, stomata research revealed that the decline of the atmospheric CO_2 concentration by about 77 ppm lagged the onset of the Younger Dryas cooling by about 130 years [28]. Interestingly, satellite measurements at the ocean-atmosphere interface show that atmospheric CO_2 concentration changes follow those in temperature by five to six months [63]. This temperature-dependent $CO_{2(atm)}/CO_{2(water)}$ equilibrium contradicts the concept that changing CO_2 concentrations force temperature changes, but implies that the warming of the oceans, which contain about 60 times more CO_2 than the atmosphere, forces CO_2 degassing, and vice versa.

Around 1850 the Little Ice Age came to an end and the Modern Warm Period began. At the same time atmospheric CO_2 concentrations gradually increased, accelerating in the 1950s and thus alarming media and politicians to the concept of Anthropogenic

Global Warming (AGW). Indeed, the average global surface temperature increased during the 20th century by about 0.8 °C (Fig. 4), mountain glaciers and Arctic ice receded, while the atmospheric CO_2 concentration unabatedly increased. However, in a geological and historical context this warming trend with its cooling periods of 1882–1917, 1940–1975 and the present one since 1998 fits well into the cyclical natural climate variations. While the IPCC foresees a continuing warming of about 0.2 °C/decade for the 21st century [9], warming has virtually stopped after the exceptionally strong 1997/98 El Niño. Since then the global average temperature declined by a negligible 0.04 °C/decade (reported by the Met Office Hadley Centre), in spite of the 8.5% increase in the atmospheric CO_2 concentration since 1998 (Fig. 5). Whether this is merely a transient perturbance of a long-term warming trend, as seen in 1940–1975, or the beginning of a new global cooling period remains to be seen, but it queries the validity of the AGW concept.

Although the IPCC [9] concedes that the warming prior to the 1950s can be explained by known natural processes, it claims that only the man-made increase in greenhouse gas concentrations, and particularly of CO_2, can explain the warming in the second half of the 20th century. Geological and historical records do, however, not point to atmospheric CO_2 concentrations as the leading climate-forcing agent. The AGW concept is not compatible with real-world observations, but is also contested on physical and methodological grounds [64, 65]. CO_2 surely plays a (minor) role in climate forcing, but current climate conditions and their changes in the past appear to be mainly governed by other, natural mechanisms, such as solar activity and ocean currents. The IPCC exaggerates the role of CO_2 as a climate forcing agent.

6 Concluding Remarks

Throughout the Earth's geologic history the climate and atmospheric CO_2 concentrations have changed continuously. The most striking fact is that the Earth has managed to maintain throughout its entire recorded geologic history of 3.8 billion years tropospheric temperatures within the limits set by the occurrence of liquid water at its surface, despite the gradually increasing solar irradiation. Main mechanisms regulating surface temperatures are the convective heat transfer by the hydrosphere and the atmosphere from low to high altitudes, and the insulating effect of the atmosphere. This so-called «greenhouse warming» is mainly caused by water vapour and clouds and to a minor part by carbon dioxide.

During industrial times the atmospheric CO_2 concentration rose from 280 ppm to the present 394 ppm, while the average global surface temperature rose (with interrup-

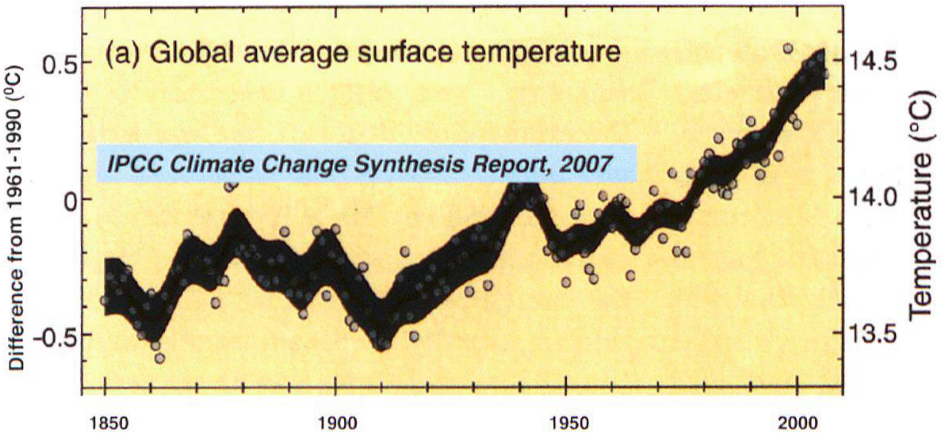

Fig. 4: Observed Changes in Global Average Surface Temperature since 1850 [9].

tions) by 0.8 °C. CO_2 concentrations notably continued to rise during the cooling phases of 1897-1917 and 1940-1975, and during the standstill of the rising global temperature since the beginning of the 21st century. The geologic record shows that through time the global temperature and atmospheric CO_2 concentration sometimes varied quite independently, but that their variations often accompanied great changes in the Earth's surface conditions. For example, during the Ordovician glaciation CO_2 concentrations were high. The Late Palaeozoic drawdown of atmospheric CO_2 was paralleled by the deposition of extensive carbonate-dominated sedimentary sequences and a gradual cooling leading to the great Gondwana glaciation. Yet, during the Early Permian, at the height of this glaciation, temperatures began to increase while atmospheric CO_2 concentrations stayed low. At the Permian-Triassic transition the CO_2 concentrations rose sharply during the development of the great Siberian flood basalt province and after the Gondwana continent had drifted out of a polar position. The Mesozoic fluctuations in the atmospheric CO_2 concentration were accompanied by the opening of new large oceanic basins during the breakup of the Pangea continent and the deposition of extensive carbonate series on large shelves in response to rising sea levels, while associated temperature variations did not correlate with changes in CO_2 concentration. Beginning in the Eocene, the steady temperature decline during the Tertiary and drawdown of atmospheric CO_2 was accompanied by further opening of the present oceans, the closure of oceanic basins, the uplift of major mountain belts, the closure of the Isthmus of Panama, and the development of gradually expanding ice shields in the Antarctic and later in the Arctic region.

The climate on Earth appears to be controlled by the interaction of external and internal forcing mechanisms. The dominant external forcing mechanism is solar irradiation that varies at different time scales in response to changes of the Earth's orbit around the Sun, and to variations in the Sun's activity that appear to be controlled by planetary tidal forces. A second external

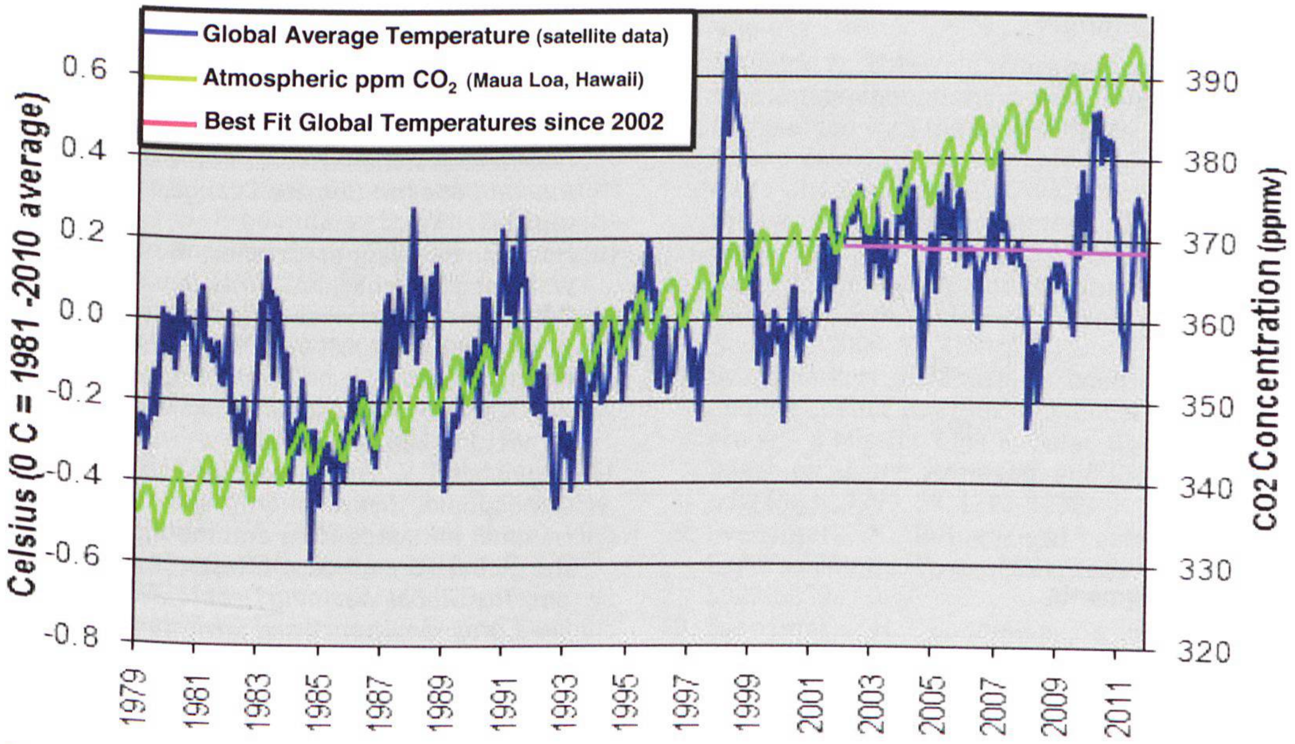

Fig. 5: Global Surface Temperature and CO_2 since 1979 [68]. The positive temperature spikes of 1998 and 2010 were caused by strong El Niños and are not related to «Global Warming», the negative spikes of 1984 and 1992 relate to the El Chicon and Pinatubo volcanic eruptions, respectively

forcing mechanism is the flux of galactic cosmic rays that reaches the Earth and appears to affect its cloud cover. This flux varies with solar activity and maybe also with the passage of the Earth through the spiral arms of the Milky Way galaxy. Internal forcing mechanisms relate to (1) the pattern of the ocean current systems, which varies at time scales of thousands or millions of years with the drifts of continents (e.g. closure of the Panama Isthmus or northward drifting of the Indian continent), but also in response to temperature changes; (2) the Earth's surface topography (e.g. mountain ranges) that is controlled by the interaction of lithospheric plates and also changes at time scales of millions of years; and (3) the composition of the atmosphere, which varies at all time scales in response to changes in surface temperatures and the biosphere, the level of volcanic activity, and since the 20th century due to anthropogenic emissions. Among the different so-called greenhouse gases, water vapour is the dominant one with CO_2 playing a subordinate role, as evidenced by the geological record and «real world» observations. – Observational empirical evidence beats modelling.

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