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Climate Change and Carbon Dioxide: Geological Perspective

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The geologic record shows that Earth's climate history is a history of constant motion and continuous change. From a geological and planetary perspective one of the most striking properties of System Earth is that throughout the whole geological history the climate variations remained always within the rather narrow temperature range at which liquid surface water can exist, at least at lower latitudes **(Fig. 1)**. The oldest known sediments were laid down 3.8 billion years ago in a marine environment by processes similar to modern sedimentation processes. The oldest evaporates formed about 3.5 billion years ago and were likewise deposited under similar conditions as evaporates precipitated in more recent times. For the first 5% of our planet's existence the geologic record is lacking, but at the beginning of the sedimentological record 3.8 billion years ago the Earth had substantial oceans with water depths up to a few kilometres, and at least a modest atmosphere. What differed in those early days was the anoxygenic atmosphere dominated by nitrogen and carbondioxide, and an energy budget very much different from today's. According to the standard model of stellar evolution the input of solar energy has since the birth of our solar system linearly *increased* by about 25%, whereas the internal heat production of the Earth through the decay of radioactive isotopes has *decreased* to less than 20% of its initial value. Still, in spite of the continuously increasing solar heat input, our planet managed to maintain throughout 3.8 billion years surface temperatures within the constraints set by the occurrence of liquid water. The combined atmosphere and hydrosphere apparently functioned as a global climate regulating system, a kind of planet-sized thermostat that prevented the planet from freezing early in her history and later counteracted the tendency of the surface temperatures to rise in response to the steadily increasing solar radiation. But the ultimate fate of our planet, maybe a billion years in the future, will be that the solar heat input will overwhelm the capacity of 'Earth's thermostat'. The oceans will evaporate, while Earth's internal heat production gradually comes to an end. Our planet will then become a hot, dry and geologically dead body, like there are many in the Universe, incapable to sustain life as we know.

3.5 Billion years ago the Earth received 20% less solar energy. Calculations indicate that at that time the radiative surface temperature should have been 10-15^{0}C lower than today. Nevertheless, the Earth's surface temperature was in fact quite similar. This is known as the

Faint Young Sun Paradox, that is generally resolved by assuming that the atmosphere of the young Earth consisted of about 25% carbondioxide and 75% nitrogen, with a much stronger greenhouse effect. If so, the initial high partial carbondioxide pressure was rapidly lowered by processes such as silicate weathering. Sediments that were deposited about 2.75 billion years ago signal that at that time the carbondioxide level had decreased to about 9000 ppm. That is about thirty times the pre-industrial level, but much less than required to defeat the faint young Sun. Maybe, the solution for the Faint Young Sun Paradox has to be sought in the surface conditions and environmental energy budget of the young Earth, which must have differed very much from today's. For example, for the first one and a half billion years or so the Earth was an oceanic planet with oceans covering most of her surface and only very little dry land. This situation lasted until about three billion years ago, when massive volumes of continental crustal material began to segregate from the Earth's mantle, gradually transforming the 'oceanic Earth' into the modern planet with continents making up about 30% of the crust. Due to the low albedo of the ocean surface, which reflects only 2% of the solar radiation, the oceanic Earth absorbed a much greater portion of the incoming solar radiation than today. Moreover, the radiogenic heat production of the ancient Earth was higher, while much heat was still left from Earth's accretionary stage. All this accounted for a much higher heat flow than today and to an intense volcanic activity emitting enormous quantities of water vapour, the strongest natural greenhouse gas. With the passage of time the Earth's mass cooled down, while solar radiation steadily increased and the evolving biosphere became an ever more important factor in regulating the surface temperature.

Not only the global temperature, but also the atmospheric carbondioxide content is continuously changing. Most of the terrestrial carbon is hosted by the mantle. Only a tiny fraction occurs as carbon compounds in the biosphere and in sediments, and as carbondioxide in atmosphere and oceans. About 1.7 billion years ago the biosphere had developed to the point at which biological photosynthesis played an important role in Earth's environment and molecular oxygen began to accumulate in the atmosphere at the expense of carbondioxide, as evidenced by the first occurrence of red beds. Ever since **(Fig. 2)** the atmospheric carbondioxide content varied continuously, but fluctuated over the last 700 million years or so always between 200 and 7500 ppm. Most of the time the content was much higher than today's extremely low level, that in geologic history is only equalled in the Late Paleozoic. The atmospheric carbondioxide content is determined by a global system of supply and extraction **(Fig. 3)**. It is continuously added to the atmosphere by degassing of the mantle and from crustal melting, as well as from ‘exchangeable reservoirs’ such as the biosphere and the oceans, and in modern time by human activities. This input is offset through uptake by oceans and withdrawal by biological, chemical and geological processes. The removed carbondioxide is sequestered as carbon and carbon compounds in sediments, biomass and limestone deposits, and is dissolved in the oceans. If all that stored carbon would be released into the atmosphere, the surface carbondioxide pressure would be at least 70 bar, that is 200 000 times the present value. Our atmosphere would then resemble that of Venus – apart, of course, from the absence of water on Venus. The inputs and outputs are more or less closely balanced and the whole geological-biological control system tends to adjust itself in a geologically short time. From the end of the 19th century atmospheric carbondioxide has grown uninterruptedly from the pre-industrial 280 ppm to the present level of nearly 400 ppm, and the increase is continuously going on at an average rate of about 2 ppm per year. The simultaneous gradual change in the carbon isotope ratio of atmospheric carbondioxide is generally interpreted as indicating that this rise is mainly or entirely due to man-made emissions. Since the beginning of the 20th century about 740 gigaton of carbondioxide has been added to the atmosphere, but this is only half of the cumulative release from fossil fuel burning, cement facturing, and oxidation of organic matter exposed by soil tilling and deforestation. Natural processes have thus taken care of the other half, through uptake by oceans and the biosphere (mostly forests of boreal and temperate zones, and oceanic plankton), through weathering processes, and by unidentified sinks. This illustrates the rapid response of the natural biological-geological control system to rising carbondioxide. In this context it is noteworthy that about one fifth of the atmospheric carbondioxide, corresponding to about 600 gigaton, is annually exchanged with natural sinks while the annual man-made emissions amount to 32.5 gigaton. Calculations based on carbon isotope ratios and mass balance suggest that less than 10% of the current atmospheric carbondioxide is man-made.

In the context of the natural variation through geologic time the modern rise of atmospheric carbondioxide is not impressive. Nevertheless, there is some fear that a continuous rise may lead to acidification of ocean water, with serious consequences for marine life, particularly corals. IPCC claims in its last report that the average acidity decreased since pre-industrial time by about 0.1 unit from the average pH of 8.15, and predicts that the ongoing growth of carbondioxide will reduce the acidity of ocean water in this century further by 0.14 to 0.35 units. If so, this is still within the observed natural variation of the present-day oceans, in which the pH ranges from about 8.3 to 7.7. But the oceans are not filled with distilled water:

they contain buffers that counteract acidification, such as the carbonic acid/carbonate equilibrium, a multitude of clay minerals, and the basaltic floor of the oceans. Interestingly, considerably higher atmospheric carbondioxide levels than the currently prevailing one **(Fig. 2A)** did not impede the formation in Cambrian time of calcitic reefs built by the skeletons of marine organisms, nor in Triassic time the first development of coral reefs consisting of aragonite (which converts to calcite upon burial).

Carbondioxide and water vapour are the most important natural greenhouse gases in the atmosphere. Together they are responsible for virtually the entire greenhouse warming. The effect of water vapour is far stronger than that of carbondioxide, but there is still dispute about their specific contributions to the total greenhouse warming. The quoted percentages range from 36 to 95% for water vapour and clouds, and from 4.2 to 26% for carbondioxide. It should be noted that the total natural greenhouse warming must be less than the generally accepted 33^0 centigrade, which number is obtained by treating the Earth as a flat black body without atmosphere and oceans that reflects 30% of the incoming solar radiation as infrared radiation. But our planet is a globe with oceans, atmosphere and biosphere, not a flat black body, so the effective natural greenhouse warming must be lower than 33^0 centigrade.

The warming effect of carbon dioxide decreases logarithmically with increasing concentration. A doubling of the pre-industrial atmospheric concentration would, if no feedbacks are involved, lead to a global temperature rise of at most 1.1^0C, not very impressive in geological context. The much higher warming of 2.0^0 to 4.5^0C projected for a doubling of the carbondioxide concentration by the IPCC General Circulation Models results from the introduction of positive feedbacks in the complex climate system, but these positive feedbacks are widely disputed. The basic physics underlying the IPCC models do make sense, but their projections depend entirely on the parameters with which the computers are fed. Not all climate-controlling factors can be adequately quantified or are fully known, nor is there any certainty that non-linear or possible chaotic forcings and feed-back mechanisms that Nature self employs have not been neglected. As long as this is the case, the projections create a virtual reality. Contrary to the short-term weather predictions for which the models can be developed and corrected by trial and error, the long-term climate models cannot be tuned any faster than the evolution of climate itself.

The fundamental assumption that the atmospheric carbondioxide concentration is the driver of global temperature, is not borne out when tested against real world data. For example, around 1850 the Little Ice age came to an end and the Modern Warm Period began. The atmospheric carbondioxide began to rise and continues to do so uninterruptedly ever since. The average global surface temperature rose **(Fig. 4)** during the 20th century by about 0.8^0C, but with cooling intervals between 1882-1917 and between 1940-1975 without any interruption in the carbondioxide growth. Both cooling periods can not be modelled. In geological and historical context the present warming trend fits well into the past climate variation. The IPCC foresees for the 21st century a continuing warming of about 0.2^0C per decade, but the warming has instead virtually stopped 15 years ago – since 1999 a negligible average rise of only 0.05^0C was measured. This happens in spite of the continuous growth of atmospheric carbondioxide by about 8.5% over the last 15 years. Whether the end of the rise of global temperature in 1999 is merely a transient perturbance of ongoing warming, like the earlier cooling intervals, or the beginning of a new global cooling period remains to be seen, but it calls into question the validity of the leading role attributed to carbondioxide in the IPCC climate models.

Back in time, the temperatures at the peak of the Medieval Warm Period in the 11th and 12th century were at least as high as today and probably higher, but stomatal density of leaves preserved in peat and lake deposits indicate that the carbondioxide level never rose above 315 ppm. That is much below the present level of nearly 400 ppm that according to the IPCC is responsible for the current warming. When we penetrate deeper into the past, the IPCC models are inadequate in reproducing past climates. The more so as we are going further back in time, because of the increasing difference in topography and environmental conditions. For example, during the Middle Pliocene, 3.3 to 3.0 million years ago, the atmospheric carbondioxide content did not much differ from that today, whereas the average global surface temperature was about three degrees centigrade above the present one. As most climatic boundary conditions were very similar to those of today, this warm period is often cited as a geological analogue of the Modern Warm Period. However, the IPCC models cannot reproduce adequately the actual climatic conditions at that time -- that would require at least a twice as high carbondioxide level. The whole geologic record reveals numerous fluctuations both in global temperature and in atmospheric carbondioxide, sometimes correlated and sometimes not. For example, in Late Ordovician time **(Fig. 2B)** there was an important glaciation under a carbondioxide level that was about 15 times higher than the pre-industrial level, while it stayed at the lowest level in geologic history during the glacial epochs in the Late Paleozoic and in our time.

We are living in the glacial epoch that began 28 million years ago with the development of the Antarctic ice cap. The earliest recorded glaciation in Greenland was between ten and six million years ago, but the build-up of ice gained momentum around three million years ago with the final closure of the Isthmus of Panama and the resulting cooling of the North Atlantic due to the global change in ocean circulations. Ice cores and sedimentary sequences reveal a climatic oscillation of glacial and interglacial episodes that reflect the astronomical Milankovitch cyclicity, with temperature fluctuations of five to six degrees centigrade. Air bubbles in Antarctic ice cores show that for the last 450.000 years the air contained approximately 100 ppm less carbondioxide during the glacials than during the interglacials, but the changes in carbondioxide content lag behind the changes in temperature with a delay of a few hundred years. Similarly, satellite measurements at the ocean-atmosphere interface show that changes in atmospheric carbondioxide concentration follow those in temperature by five to six months. This temperature-dependent equilibrium between carbondioxide in water and in the atmosphere contradicts the concept that changing carbondioxide concentrations force temperature change. It implies that warming of the oceans, which contain about 60 times more carbon dioxide than the atmosphere, forces the degassing of carbondioxide into the atmosphere.

In conclusion, data from the historical en geologic record as well as real world observations cast doubt on the leading role attributed by the IPCC to carbondioxide as the principal climate forcing agent on the base of assumed feedbacks. Carbondioxide undoubtedly plays a minor role in climate regulation because of its net radiative forcing, but the feedbacks are clearly exaggerated. The climatic conditions are mainly governed by other mechanisms.