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Homo Sapiens, the Anthropocene Carbon Oxidation Event and the Shift in the State of the Atmosphere

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Abstract

Since the mid-1970s the Earth's atmosphere-ocean system has entered unchartered territory, with greenhouse forcing rising at a geologically unprecedented pace of c.2.0 ppm/year tracing into early Pliocene-like conditions (c.400 ppm CO_2). Mean global temperature lag effects are tracking toward 3-4 degrees C and sea level toward 25+/-12 meters. Depending on the scale of further emissions and land clearing, feedbacks from melting ice/warming water interactions and from methane release, conditions may approach those of the PETM (Paleocene-Eocene Thermal Maximum) 55 million years ago, when release of c. 2000 billion tons of carbon resulted in c. 5 degrees C temperature rise and a mass extinction of species. Oxidation of available fossil fuel reserves of c. 6000 billion ton carbon (GtC), deforestation and burning of vulnerable vegetation, and release of metastable methane pools result in a decrease in atmospheric oxygen level on the scale of a couple of percent, followed by further long term depletion depending on the intensity of carbon cycle, methane release and ice melt feedback processes.

1. INTRODUCTION

The mastery of fire by Homo sapiens about 800,000 years ago or earlier, a power not possessed by other species, has led inexorably to large scale modification of the planetary environment, culminating in geological scale transformation defined in terms of a new era—the Anthropocene, defined alternatively since the down of agriculture (Ruddimann, 2005) or of the industrial age (Steffen et al., 2008). This article compares aspects of geological crises and their driving forces with current climate changes. Of all the factors which underlie mass extinctions of marine and continental plants and animals, sharp rises in atmospheric greenhouse gases (carbon dioxide, methane, nitric oxide) are probably the most important in view of their centuries to millennia or longer-term consequences. Closely associated with runaway climate change are acidification and anoxia of the hydrosphere. A release of carbon on a scale equivalent to the world's known fossil fuel resources (>6000 billion ton carbon [GtC]) triggering CO_2 and methane feedbacks from the ocean, the biosphere and melting permafrost, will accentuate the current mass extinction of species toward the scale of the Paleocene-Eocene thermal maximum (PETM: c.55 million years (Ma) ago when c. 2000 GtC were released as methane (Zachos et al., 2008). Potentially the scale of the runaway greenhouse effect may reach that of the K-T impact boundary 65 million years ago, when 4600 GtC are estimated to have been released in connection with an asteroid impact (Beerling et al., 2002).

2. CO_2 AND THE ATMOSPHERE

Lost all too often in the climate debate is an appreciation of the delicate balance between the physical and chemical state of the atmosphere-ocean-land system and the evolving biosphere, which controls the emergence, survival and demise of species, including humans. By contrast to Venus, with its thick blanket of CO_2 and SO_2 greenhouse atmosphere, exerting extreme pressure (90 bars) at the surface, or Mars with its thin (0.01 bar) CO_2 atmosphere, the presence in the Earth's atmosphere of trace concentrations of greenhouse gases (CO_2, methane, nitric oxides, ozone) modulates surface temperatures in the range of -89 and +57.7 degrees Celsius, with a mean of 14 degrees C, allowing the presence of liquid water and thereby of life. Forming a thin breathable veneer, only slightly more than one thousandth the diameter of Earth and evolving both gradually as well as through major perturbations with time, the Earth's atmosphere acts as a lungs of the biosphere, allowing an exchange of carbon gases and oxygen with plants and animals which, in turn, affect the atmosphere, for example through release of methane and photosynthetic oxygen (Figure 1). As testified by the geological record nearly all of the previous mass extinctions of species through the history of Earth have been associated with a rise in CO_2 (Figure 2), methane or H2S, injection of aerosol and dust, acidification of the oceans and anoxia (Stanley, 1987; Ward, 1994, 2007; Sepkoski, 1996; Keller, 2005; Zachos et al., 2001, 2008; Glikson, 2005, 2008; Veron, 2008).

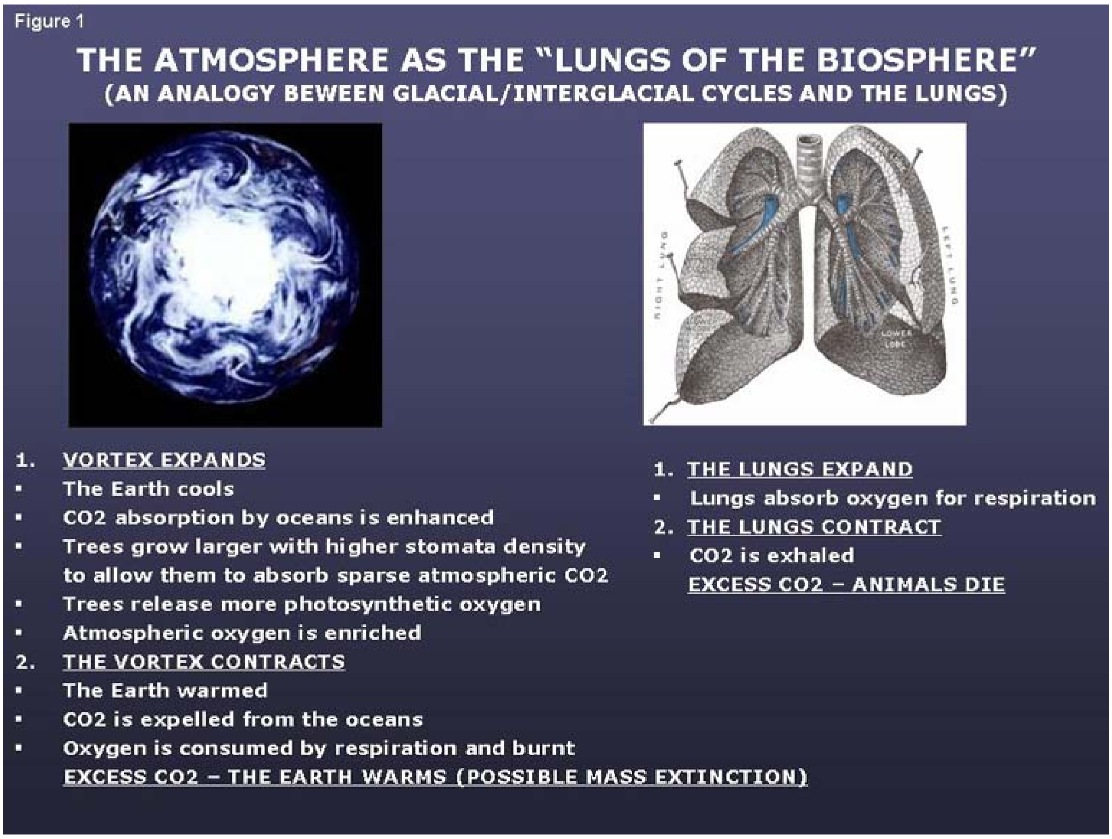


Figure 1. The terrestrial atmosphere as "lungs of the biosphere" – an analogy.

Figure 2

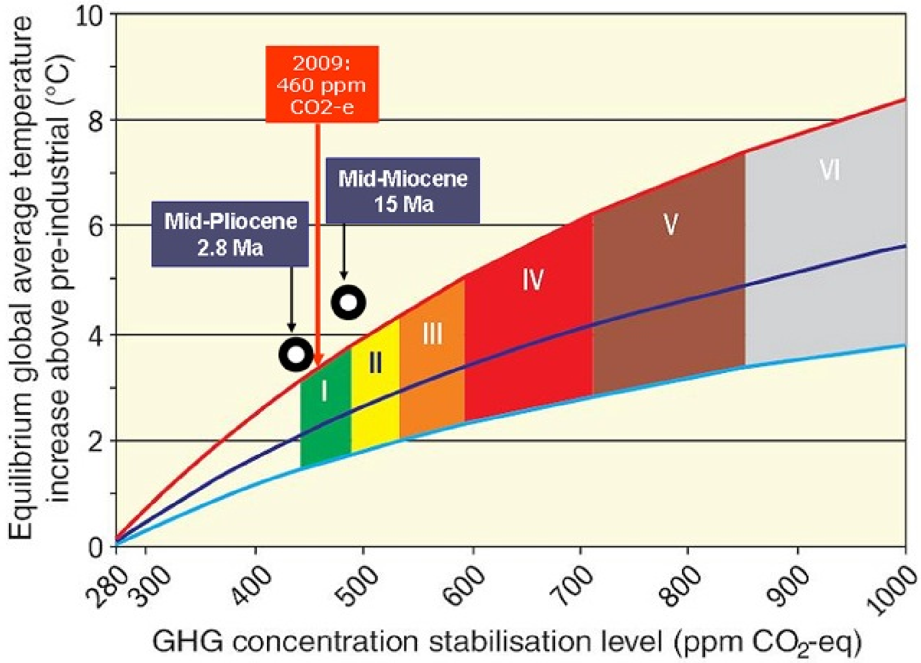


Figure 2. The relations between atmospheric CO2-equivalent (including the radiative forcing of methane) and mean global temperature, according to Charney's climate sensitivity parameter (Hansen et al., 2007, 2008) (IPCC-2007). Circles mark new paleoclimate estimates of atmospheric conditions in the mid-Pliocene (2.8 million years ago) and the mid-Miocene (15 million years ago), with implications to current climate trajectories.

During most of Earth history the oxygen-poor composition of the atmosphere resulted in dominance of reduced carbon species in the air and the oceans, including methane, carbon monoxide and hydrogen sulphide, restricting habitats to algae and bacteria (Kasting, 2005). An oxygen enrichment pulse occurred about 2.4 billion years ago (Ga), likely oxidizing atmospheric methane and leading to the Huronian ice age. About 0.7 Ga, in the wake of the Marinoan glaciation (so-called "Snowball Earth") (Hoffman, 2009), an oxygen-rich cold hydrosphere allowed development of oxygen-binding proteins and thereby of multicellular animals, followed by development of a rich variety of organisms in the so-called "Cambrian explosion" c. 542 million years ago (Ma) (Gould, 1989). The concentration of greenhouse gases in the atmosphere exerts radiative forcing which modulates temperatures and, in turn, generates feedbacks from the hydrosphere and the biosphere. The "albedo-flip" process (Hansen et al., 2007, 2008) involves release of CO_2 from warming water, ice melt/warm water interaction, decline of ice reflection (albedo) and increase in infrared absorption by exposed water. Further release of CO_2 from the oceans and from drying and burning vegetation shifts global climate zones toward the poles, warms the oceans and induces ocean acidification (Hansen et al., 2007, 2008; Veron, 2008). The essential physics of the infrared absorption/emission resonance of greenhouse molecules, indicated by observations in nature and laboratory studies, is portrayed in the relations between atmospheric CO_2 and mean global temperature projections (Figure 2).

CO_2 is 28 times more soluble in water than is oxygen, where declining pH below 8.2 results in replacement of the carbonate ion (CO3-2) with bicarbonate ion HCO3-1 and carbonic acid (H2CO3), which marine organisms such as benthic fauna and corals can not use for calcification. Above critical threshold CO_2 becomes toxic for certain organisms, excess CO_2 reduces the ability of respiratory pigments to oxygenate tissues, and makes body fluids more acidic, thereby hampering the production of carbonate hard parts like shells. Relatively modest but sustained increases in CO_2 concentrations hamper the synthesis of proteins, reduce fertilization rates, and produce deformities in calcareous hard parts. The observed pattern of marine extinctions is consistent with hypercapnia (excessive levels of CO_2), with related extinction events (Ward, 2007). Close correlations are recorded between peak CO_2 events and mass extinction of species through time (Figure 3).

Figure 3

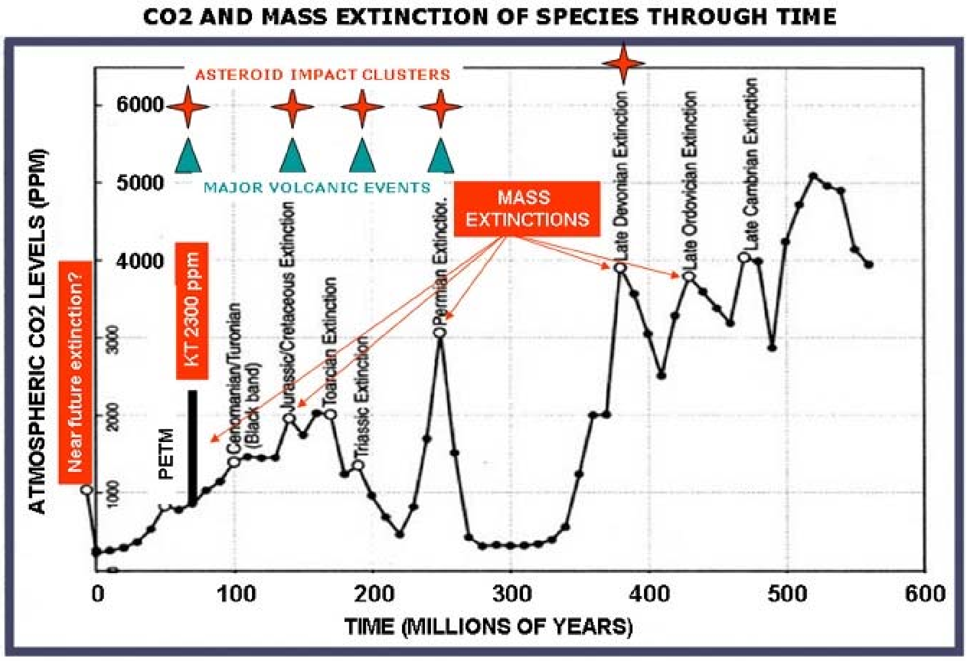


Figure 3. Major mass extinctions in the history of Earth were related, among other factors, to runaway rise in the level of atmospheric CO2. After Ward, 2007.

3. CAINOZOIC CLIMATES AND HUMAN PREHISTORY

The present state of the biosphere, allowing the flourishing of large mammals and of humans on the continents, developed when CO_2 levels declined gradually through the upper Eocene (50-34 Ma) and fell sharply to below about 500 ppm by the end of this period at 34 Ma (Royer, 2006; Zachos et al., 2001, 2008) (Figure 4), triggering formation of the Antarctic ice sheet. A significant factor in the formation of the latter is the opening of the Drake Passage between South America and West Antarctica, which allowed the establishment of the circum- Antarctic current, isolating the continent from warm currents emanating at low latitudes. This period saw a large impact cluster, including the Popigai, Chesapeake Bay and Mount Ashmore mega-impacts (Koeberl and Montanari, 2009). Global thermal rises occurred in the Oligocene (c. 25 Ma) and mid-Miocene (c. 15 Ma), when large parts of the Antarctic ice sheet melted. In the wake of a thermal rise about 3.0 Ma (mid-Pliocene) of c. 3–4 degrees C (relative to preindustrial), further global cooling resulted in formation of the Greenland ice sheet and the Arctic Sea ice, with further decline in global temperatures (Figure 4).

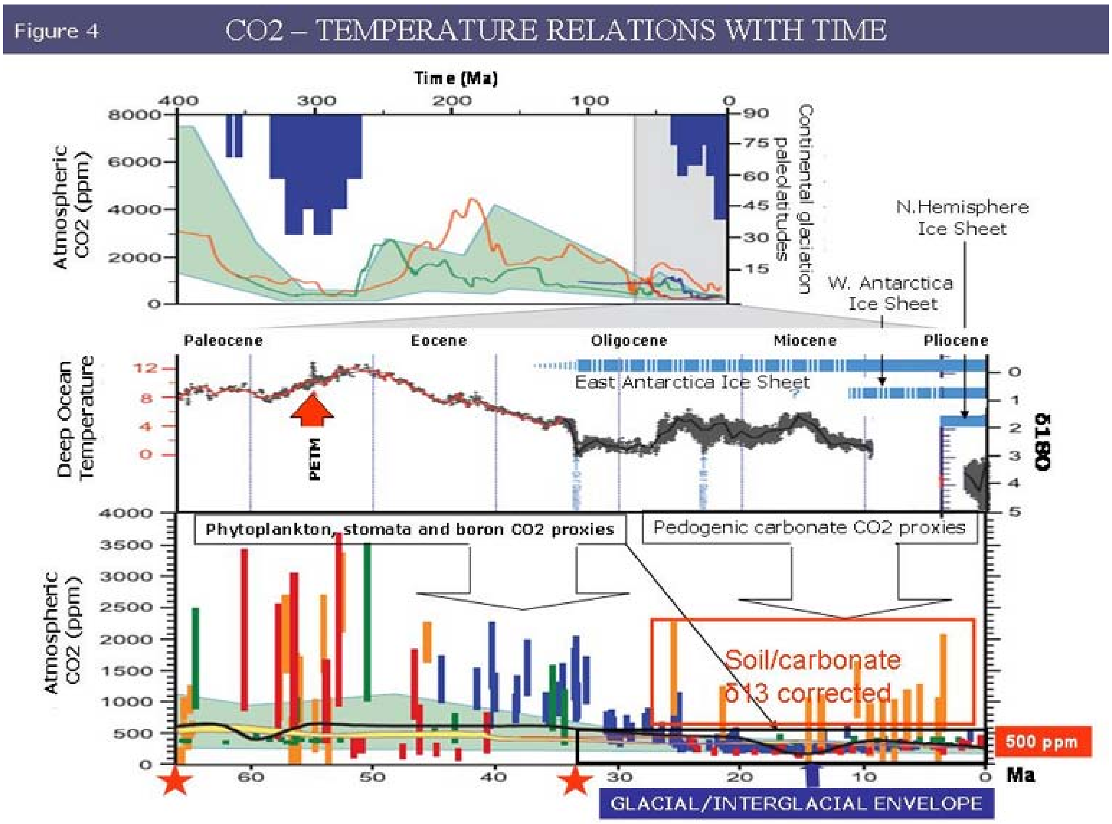


Figure 4. CO2 and deep ocean temperature changes during the Cainozoic (since 65 million years-ago [Ma]), based on proxy studies (stomata fossil leaf pore densities; 13C isotopes in carbonate nodules in fossil soil), indicating the onset age of the Antarctic ice sheet (c. 34 Ma), West Antarctic ice sheet and Northern Hemisphere ice sheets (c. 3 Ma). Note the glacial-interglacial approximate upper limits at 500 ppm CO2 (after Zachos et al. 2008).

Figure 5

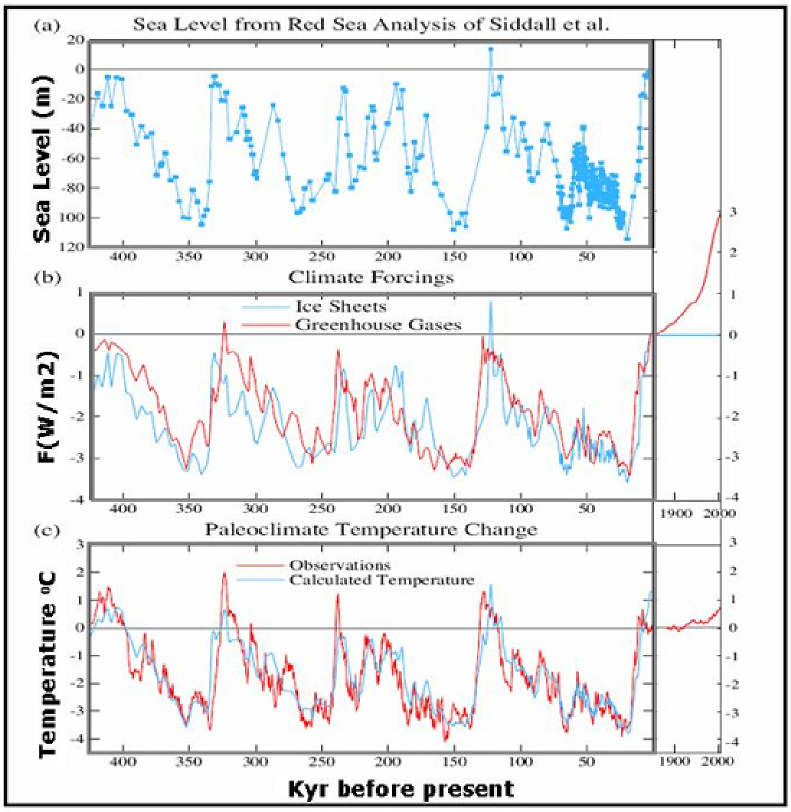


Figure 5. Milankovic cycles over the last 420 kyr, showing (a) sea levels from Red Sea analysis by Siddall et al.; (b) forcing values in Watt/m2 for the ice albedo flip and for greenhouse gases; (c) temperatures observed through proxies and model calculated. After Hansen et al. 2007 and 2008.

The increase in the size of ice sheets during the Pleistocene (1.8 Ma to 10 kyr) was intimately associated with increasing amplitude of glacial-interglacial cycles (Milankovic cycles; Roe, 2006), the main period of advanced human evolution.

The change about 1.0 Ma from cycle frequency of about 41,000 years to a frequency of about 100,000 years (Figure 5) resulted in extreme glacialinterglacial cycles of +/-5 degrees C, with glacial terminations triggered by orbital forcing peaks of 40 – 60 Watt/m2 at mid-northern latitudes. Inherent in the Milankovic cycles are strong ice melt feedbacks which amplify glacial melting through the albedo-flip process. This involves reflection of total radiative spectra and concomitant absorption of the infrared thermal spectra by melt water which form above ice as well as at lateral ice-water interfaces (Hansen et al., 2007). Detailed studies of Greenland and Antarctic ice cores indicate rapid albedo-flip process down to time scales of decades and even a few years (Steffensen et al., 2008). The reverse, ice freezing events, can occur equally fast. The warming of the oceans and release of CO_2 from water and from drying biosphere lag behind albedo-flip events by about 800 years (Hansen et al., 2007). This ensues in oscillation of CO_2 levels between glacial states of c. 180 ppm and interglacial states of c.280-300 ppm, corresponding mean global temperature changes of +/- 4 to 5 degrees C and sea level changes on the scale of +/- 100 meters (Figure 5). Human evolution during the Pliocene-Pleistocene periods is closely controlled by climate changes, including an overall cooling trend inherent in which is an increase in climate variability following the stages (Figure 6: deMenocal, 2004):

A. c. 4.2 Ma: 19–23 kyr-long Milankovic orbital cycles. A change of ocean current circulation patterns, including the Humboldt Current and Gulf Stream, consequent on the rise of the central cordillera and closing of the Panama straits, which resulted in the isolation of the Pacific and Atlantic oceans.

B. c. 3.0 Ma: Thermal peak c. 3 – 4 degrees C higher than mid-20th century, related CO_2 rise (c. 400 ppm) and sea level rise (25±12 metres).

C. c. 2.8 Ma: Change from 19–23 kyr-long glacial-interglacial cycles, controlled by eccentricity modulated precession, to c. 41 kyr-long obliquity-controlled cycles, associated development of El-Nino Southern Oscillation (ENSO) cycles, increased amplitude of glacial-interglacial cycles; increased generation of dust related to drying and glacial erosion and winds.

D. c. 1.8 Ma: Increased amplitude of c. 41 kyr-long cycles associated with marked increased in the ENSO polarity, La-Nina frequency and aridity.

E. c. 0.9 Ma: Onset of c. 100 kyr-long eccentricity-controlled cycles displaying glacial interglacial temperature variations of up to 6 degrees C and glacial dust levels in marine sediments rising by up to 40 percent.

The transitions through the Pliocene and Pleistocene from tropical to savannah environments in Africa, accompanied with faunal diversification from tropical species toward arid-zone type species, including Antelopes (Bovids), about 2.8 Ma, 1.8-1.7 Ma and 0.8-0.7 Ma, signify an increase in climate variability and enhanced pace of evolution. Human evolution accords with these transitions in terms of variability selection, diversification and appearance of Olduvan stone tools from about 2.7 Ma and Acheulean stone tools from about c.1.7 Ma (deMenocal, 2004) (Figure 6).

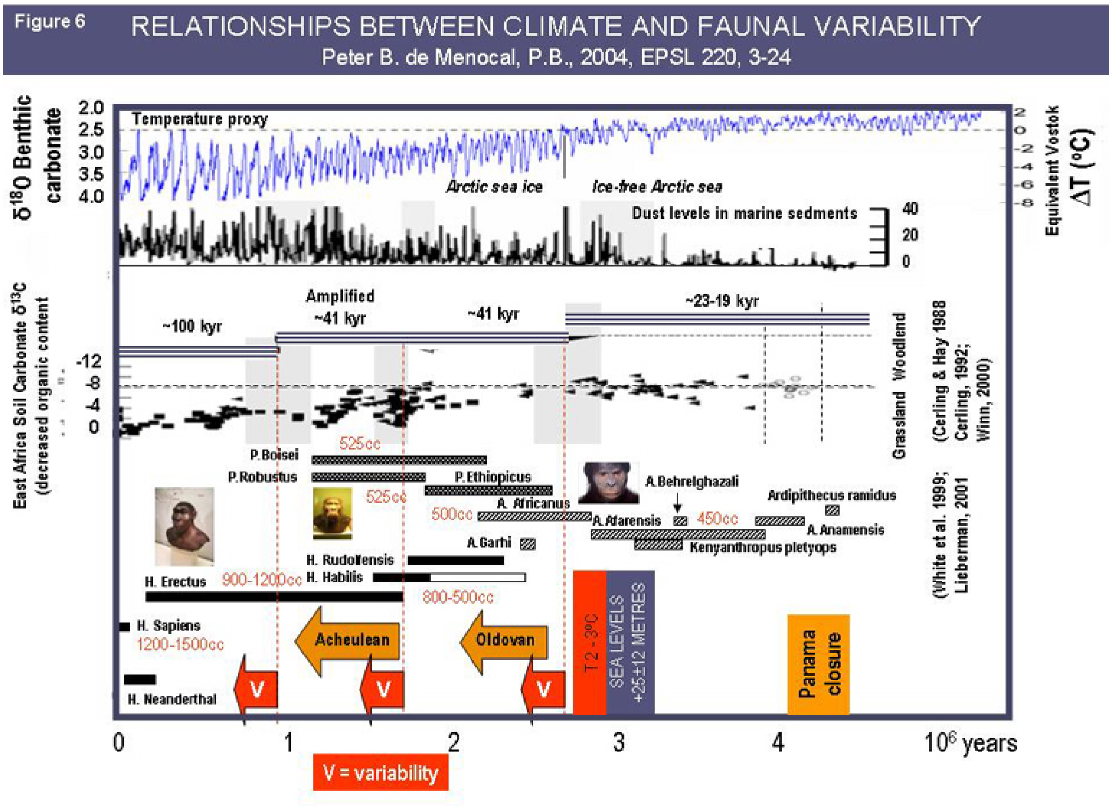


Figure 6. Human evolution in relation to the atmosphere from about 5 Ma (early Pliocene) (after deMenocal 2004). Upper blue plot represents paleo-deep sea temperature variations. Black plot represent atmospheric dustiness, corresponding to wind and glacial states. Discontinuous line below represents the duration of Milankovic cycles. Black marks below represent development of grasslands and decrease of organic productivity as the habitats shift from tropical to savannah conditions. Discontinuous lines below represent recorded durations of human species.

Survival stresses associated with extreme glacial-interglacial climate contrasts from about 0.9 Ma saw near-doubling of Homo cranial cavity (from c. 450 cc to c. 1200-1500 cc), mastering of fire and, from about 160 kyr, cultural developments including burial, ornamentation and rock painting. Stabilization of current interglacial from the last termination c. 11.7 kyr reaches the Holocene Optimum, followed by incipient effects of land clearing, land cultivation, domestication of animals and burning, regarded by Ruddiman (2003) as the early Anthropocene, expressed by limited rise of methane.

Small human clans post-3 million years-ago responded to changing climates through migration within and out of Africa. Homo sapiens emerged during the glacial period preceding the 124 thousand years-old Emian interglacial, when temperatures rose by about 1 degree C and sea levels by 4 - 6 meters relative to pre-industrial (Overpeck et al., 2006; Blanchon et al., 2009). The development of agriculture and thereby human civilization had to wait until climate stabilized about 8000 years ago, when large scale irrigation along the great river valleys (the Nile, Euphrates, Hindus and Yellow River) became possible.

4. THE ANTHROPOCENE CARBON OXIDATION EVENT

Since the down of the industrial age c. 1750, anthropogenic emission of carbon gases in excess of >370 GtC have increased the atmospheric inventory of 590 GtC to near-800 GtC, progressively changing the composition, infrared radiative forcing and thermal properties of the atmosphere. Rising at about 2 ppm CO_2/year, a pace unprecedented in the geological record, the late Anthropocene carbon oxidation event has already added more than one half of the original carbon inventory of the atmosphere and is triggering a fundamental shift in the state of the atmosphere-ocean-biosphere system. By the end of the first decade of the 21st century the deleterious effects of pollution and deforestation have reached a geological scale, tracking toward conditions which existed on Earth in the mid-Pliocene, about 2.8 million years ago (Haywood and Williams, 2005; Dowsett et al., 2005; Pagani et al., 2009).

Figure 7

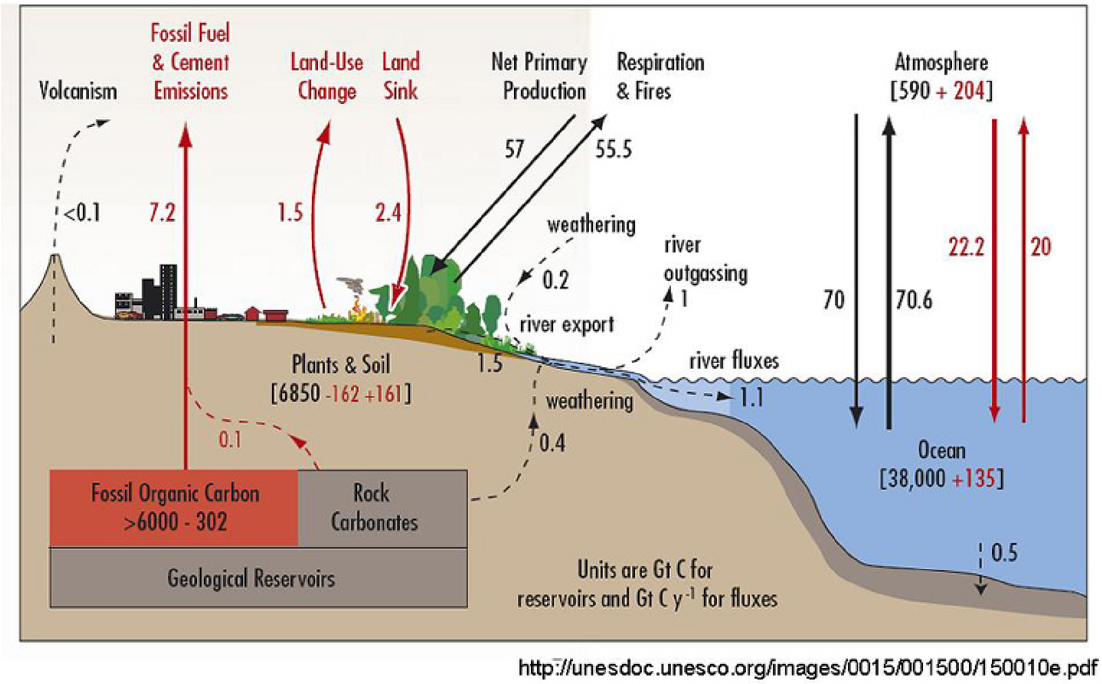
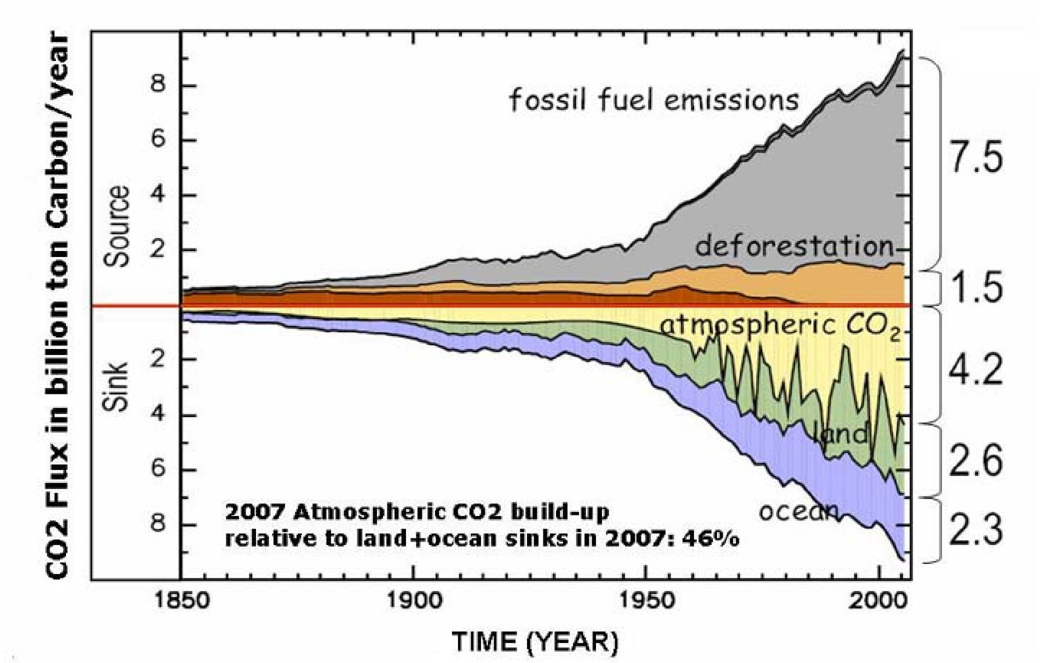


Figure 7. The terrestrial and marine carbon cycle estimated for 2000 – 2005. Pools of carbon are in billion ton carbon (GtC) and annual fluxes in GtC/year. Background or pre-anthropogenic pools and luxes are in black while the human perturbation to the pools and fluxes are in red.
http://unesdoc.unesco.org/images/0015/001500/150010e.pdf

Figure 7 and Table 1 provide estimates of carbon mass values of the atmosphere, ocean, plants, soil, methane deposits and fossil fuel reserves. By 2007 near 46% (4.2 GtC/year) of CO_2 emitted from fossil fuel burning (7.5 GtC/year) and land clearing (1.5 GtC/year) were retained in the atmosphere, while the rest were sequestered by the oceans and vegetation (Figure 8). The scale of emissions to date (370 GtC) equals c. 5% of the carbon content of the combined plant and soil inventory (6850 GtC), near-6% of the known global fossil organic carbon reserve (>6000 GtC), c. 8% of the carbon released to the atmosphere during the K-T impact event 65 Ma ago (c. 4600 GtC) which caused c. 47% mass extinction of genera, and c. 18% of the 2000 GtC released at 55 Ma during the Paleocene- Eocene thermal maximum (PETM) (Zachos et al., 2001, 2008). Using the PETM and KT events as benchmarks of low (<10% of genera) and high (47% of genera) levels of mass extinction, from Table 1 current fossil fuel reserves and methane deposits in permafrost and shallow sediments (Figure 9) are of a magnitude whose release would trigger consequences on a scale analogous to levels which triggered abrupt climate changes and mass extinctions in the history of Earth (Figure 3).

Figure 8



http://www.globalcarbonproject.org/carbonbudget/07/files/GCP_CarbonBudget_2007.pdf

Figure 8. The relation between the magnitude and proportions of the CO2 cycle for the period 1850 – 2007 through fossil fuel emissions, deforestation, atmospheric accumulation and sequestration in the hydrosphere and land (vegetation and soil) expressed in billion tons carbon (GtC). Global Carbon Project http://unesdoc.unesco.org/images/0015/001500/150010e.pdf

Figure 9

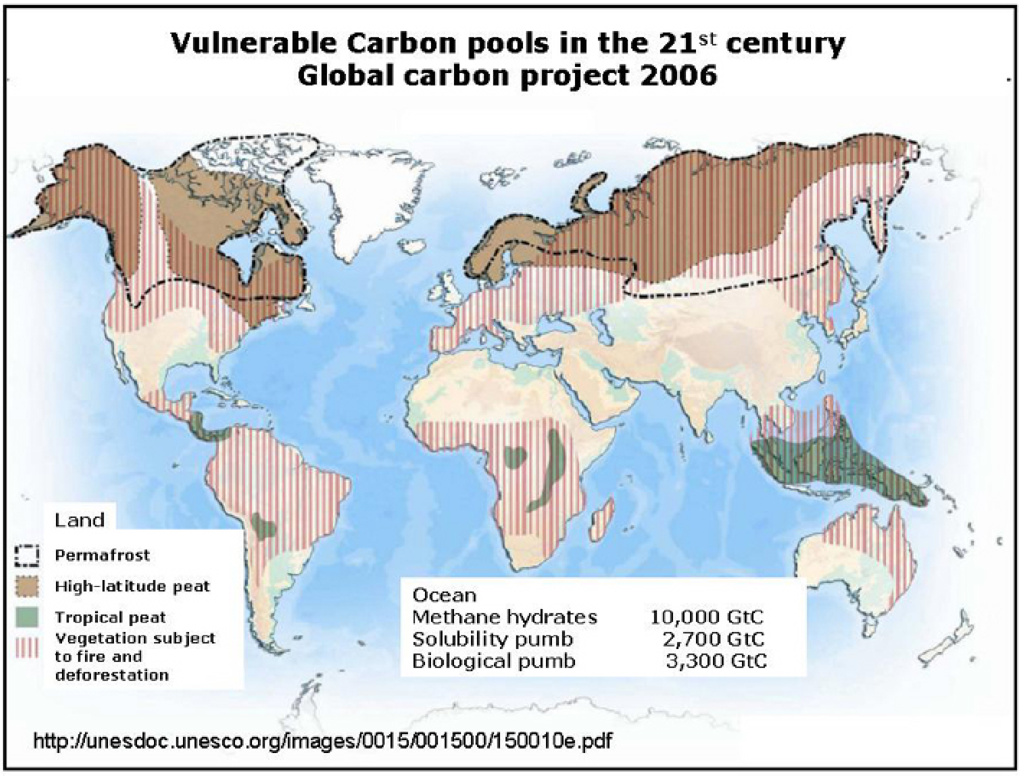


Figure 9. Vulnerable carbon pools in the 21st century.
http://unesdoc.unesco.org/images/0015/001500/150010e.pdf

From Table 1 oxidation of c. 6000 GtC fossil fuel, vulnerable vegetation and about 50% of methane pools in permafrost and peatland would consume c. 2.10^{13} tons O_2, i.e. about 1 percent of the atmospheric inventory of $1.4.10^{15}$ ton O_2. However, given an oxygen atmospheric residence time of 4500 years and an oxygen cycle in the order of 3.10^{14} ton O_2 per year for the atmosphere and biosphere, long term decline in photosynthesis would result in several percent decline in atmospheric O_2 similar to geological greenhouse states (Berner et al., 2007) (Figure 10).

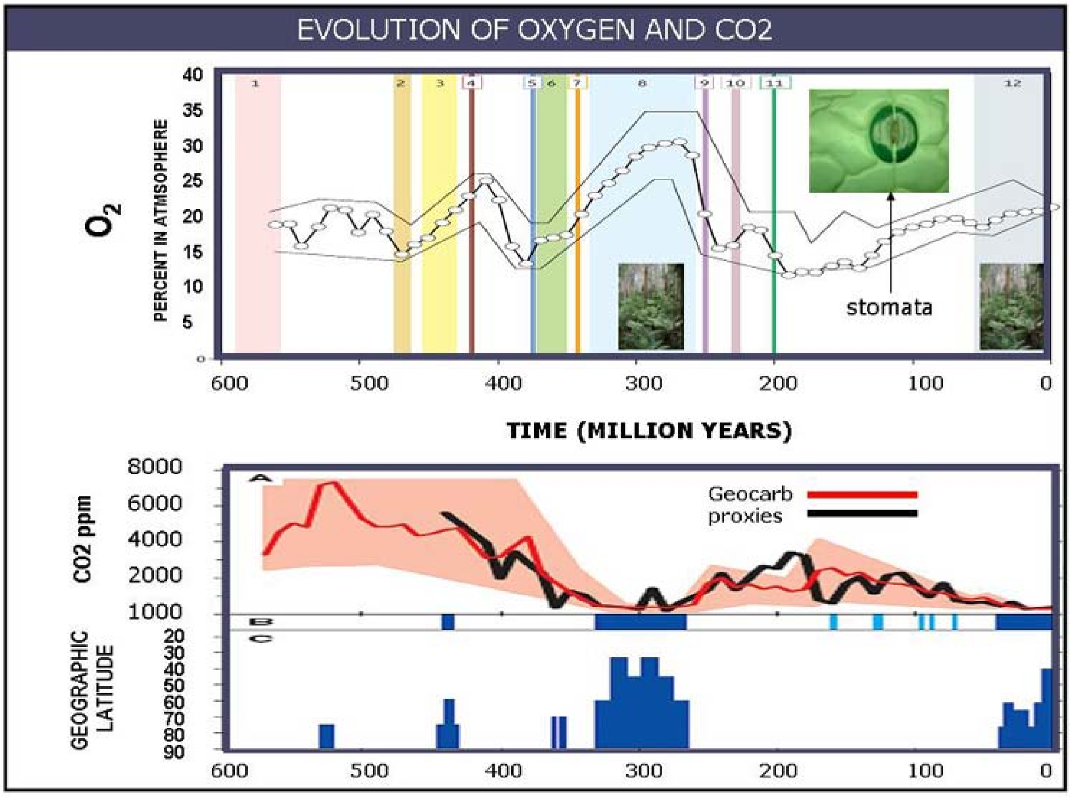
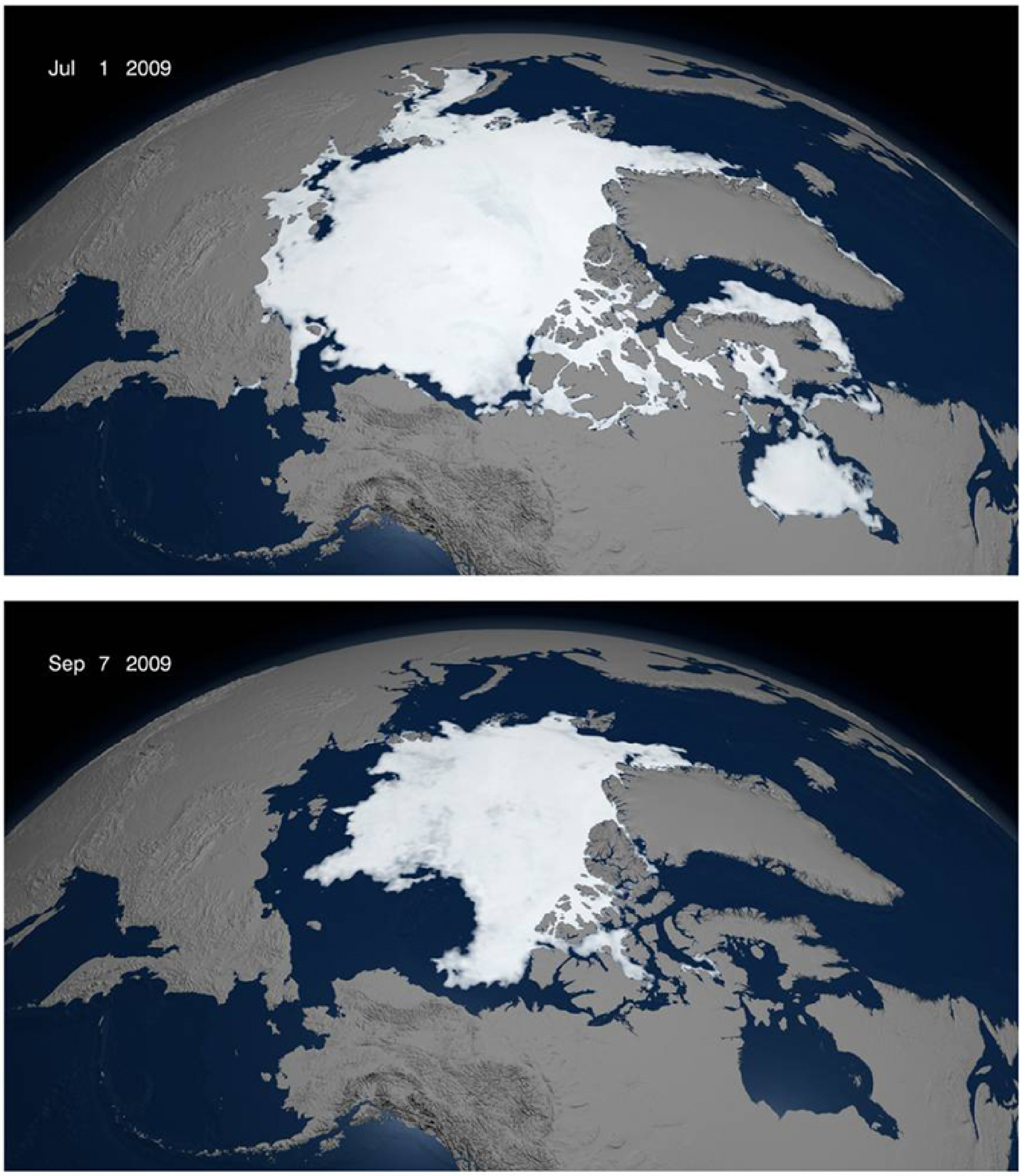


Figure 10. Proxy and model based variations in CO2 and oxygen during the last 560 million years (after Royer, 2004, and Berner et al., 2007). Blue areas represent glacial periods in terms of time and latitudinal extent. Red line on the CO2 plot represents Geocarb model estimate and black line represents proxy-based estimates.

Table 1. Carbon inventories of the atmosphere, ocean, plants, soil, methane deposits and fossil fuel reserves and corresponding CO_2 and O_2 levels. The Global Carbon Cycle. UNESCO-SCOPE. 2006.

Ocean-land-atmosphere-biosphere system	GtCarbon	Equivalent $GtCO_2$	Oxygen combined to form CO_2 (in GtO)
Deep ocean	38,000+135	c.140,000	c. 100,000
Atmosphere	590+204	c.2900	c. 2100
Plant and soil	6850	c.25,000	c. 18,000
Vegetation subject to fire and/or deforestation	650	2380	c.1730
Total fossil fuel	>6000 - 302	c.22,000	c.16,000
Methane in Permafrost	900	c.3300	c.2400
Methane in high-latitude peatland	400	c.1460	c.1060
Methane in tropical peat	100	c.370	c.270
Methane in ocean hydrates	10,000	c.37,000	c.27,000
Carbon in solubility Pump	2700		
Carbon in biological pump	3300		

Since the 18th century mean global temperature has risen by about 0.8^{o}C. Another 0.5^{o}C is masked by industrial-emitted sulphur aerosols, and further rise is inherent in current melting of the ice sheets and sea ice. The polar regions, acting as “thermostats” of the Earth as the source of the cold air current vortices and cold ocean currents, such as the Humboldt and California current, are warming at a rate 3 or 4 times as fast as lower latitude zones (http://data.giss.nasa.gov/gistemp/). The most detailed satellite information available shows that ice sheets in Greenland and western Antarctica are shrinking and in some places are already in runaway melt mode.



Late summer 2009 shrinking of the Arctic Sea ice (NASA).

A new study, using 50 million laser readings from a NASA satellite, calculates changes in the height of the vulnerable but massive ice sheets and found them especially worse at their edges, where warmer water eats away from below. In some parts of Antarctica, ice sheets have been losing 30 feet a year in thickness since 2003.

A rise of atmospheric CO_2 concentration triggers feedback effects due to warming, desiccation and burning of vegetation, further releasing CO_2. The onset of methane release from polar bogs and sediments is of major concern. Because CO_2 is cumulative, with atmospheric residence time on the scale of centuries to millennia, stabilization of the climate through small incremental reduction in emission may not be sufficient to avoid runaway climate change and possible tipping points (Lenton et al., 2008).

Sea level rise constitutes the definitive parameter reflecting all other components of climate change. Since the early 20th century the rate of sea level rise increased from about 1 mm/year to about 3.5 mm/year (1993 – 2009 mean rate 3.2+/-0.4 mm/year) (Rahmstorf, 2007), representing a nearly 4-fold increase in the rate of global warming since the onset of the industrial age. According to Overpeck et al. (2008) “Sea-level rise from melting of polar ice sheets is one of the largest potential threats of future climate change. Polar warming by the year 2100 may reach levels similar to those of 130,000 to 127,000 years ago that were associated with sea levels several meters above modern levels; both the Greenland Ice Sheet and portions of the Antarctic Ice Sheet may be vulnerable. The record of past ice-sheet melting indicates that the rate of future melting and related sea-level rise could be faster than widely thought."

The world is in a lag period, when increasing atmospheric energy is expressed by intense hurricanes, increased pressure at mid-latitude high pressure zones and shift of climate zones toward the poles. With ensuing desertification of temperate zones, i.e. southern Europe, southern Australia and southern Africa, the desiccated forests become prey to firestorms, such as in Victoria and California. Feeble attempts by civilization to mitigate the climate are drowning in a tide of medieval conspiracy theories by vested interests and fundamentalist man-overnature ideologues (Hamilton, 2010; Hoggan, 2009). There is nowhere the 6.5 billion of contemporary humans can go, not even the barren planets into the study of which space agencies have been pouring more funding than governments allocate for environmental mitigation to date. At 460 ppm CO_2- equivalent, the climate is tracking above conditions which existed during the early and mid-Pliocene, raising sea levels by 25+/-12 meters (Haywood and Williams, 2005) and close to the upper stability limit of the Antarctic ice sheet, defined at approximately 500 ppm (Zachos et al. 2001, 2008; Royer, 2006). Once transcended, mitigation measures would be unable to re-form the cryosphere. Summing up, Hansen et al. (2008) state "If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects."

> "We're simply talking about the very life support system of this planet." (Joachim Schellnhuber, Director, Potsdam Climate Impacts Institute, advisor to the German government).

References

Beerling, D.J., Lomax, B.H., Royer, D.L., Upchurch, G.R. and Kump, L.R., (2002). An atmospheric pCO_2 reconstruction across the Cretaceous-Tertiary boundary from leaf megafossils. Proceedings National Academy of Science 99, 7836–7840.

Berner, R.A., Vandenbrook, J.M., Ward, P.D. 2007. Oxygen and evolution. Science 316, 557-558.

Blanchon, P., Eisenhauer, A., Fietzke, J., and Volker, L., (2009). Rapid sea-level rise and reef back-stepping at the close of the last interglacial high stand. www.nature.com/doifinder/10.1038/nature07933

deMenocal, P.B., (2004). African climate change and faunal evolution during the Pliocene-Pleistocene. Earth Planetary Science Letters 220, 3–24.

Dowsett, H.J., Chandler, M.A., Cronin, T.M., Dwyer, G.S., (2005). Middle Pliocene sea surface temperature variability. Paleoceanography 20, PA2014.

Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S. J., Jouzel, J., Masson- Delmotte, V., Popp, T., Rasmussen, S. O., Rothlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M.L., Sveinbjörnsdóttir, A. E., Svensson, A., White, W. C., 2008. High-resolution Greenland ice core data show abrupt climate change happens in few years. Science Express 19 June 2008 / Page 1/ 10.1126/science.1157707

Glikson, A.Y., (2005). Asteroid/comet impact clusters, flood basalts and mass extinctions: Significance of isotopic age overlaps. Earth and Planetary Science Letters 236, 933– 937.

Glikson, A.Y., (2008). Milestones in the evolution of the atmosphere with reference to climate change. Australian Journal of Earth Science, 55, 125-139.

Hamilton, C., (2010). A Requiem For A Species. Allen&Unwin, Sydney. 286 pp.

Gould, S.J., (1989). Wonderful Life (W.W. Norton, 1989), ISBN 0-393-02705-8

Hansen, J., Mki. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, (2008): Target atmospheric CO_2: Where should humanity aim? Open Atmospheric Science Journal 2, 217- 231

Hansen, Sato, M., Kharecha, P., Russell, L., Lea, D.W. and Siddall, M., (2007). Climate change and trace gases. Philosophical Transaction of the Royal Society A 365, 1925-1954.

Haywood, A. and Williams, M., (2005). The climate of the future: clues from three million years ago. Geology Today, 21, 138-143

Hoffman, P., (2009). Pan-glacial—a third state in the climate system. Geology Today 25, 107-114.

Hoggan, J., (2009). Climate Cover-Up. Greystone Books, Vancouver. 241 pp.

Kasting, J.F., (2005). Methane and climate during the Precambrian era. Precambrian Research 137, 119–129.

Keller, G. (2005). Impacts, volcanism and mass extinction: random coincidence or cause and effect? Australian Journal of Earth Science 52/4, 725-757.

Koeberl, C. and Montanary, A. (eds.), (2009). The Late Eocene Earth: Hothouse, icehouse, and Impacts. Geological Society of America, Special Paper 452, 322 + viii pp.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Science, 105, 1786–17936.

Overpeck, J.T., Otto-Bliesner, B.L, Miller, G.H., Muhs, D.R., Alley, R.B., Kiehl, J.T., (2006). Paleoclimatic evidence for future ice-sheet instability and rapid sea level rise. Science 311, 1747–1750.

Pagani, M., Zhonghui, L., LaRiviere, J., Christina A. R., (2009). High Earthsystem climate sensitivity determined from Pliocene carbon dioxide concentrations. Nature Geoscience 3, 27-30.

Rahmstorf S.R. 2007. A semi-empirical approach to projecting future sea level rise. Science, 315, 368-370.

Roe, G., (2006). In defense of Milankovitch. Geophysical Research Letters 33, L24703.

Royer, D. L., (2006). CO_2-forced climate thresholds during the Phanerozoic. Geochim. Cosmochim. Acta, 70, 5665–5675.

Ruddimann, W.F., (2005). Plows, Plagues, and Petroleum: How Humans Took Control of Climate, Princeton University Press.

Sepkoski, J. J. Jr., (1996). Patterns of Phanerozoic extinction: a perspective from global data bases. In: Walliser O. H. ed. Global Events and Event Stratigraphy, 35 – 52. Springer-Verlag, Berlin.

Stanley, S.M., (1987). Extinctions. Scientific American Library, New York.

Steffen, W, Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature? Ambio 36, 614-621.

Steffensen, J.P., et al., (2008). High-Resolution Greenland Ice Core Data Show Abrupt Climate Change Happens in Few Years. Science Express, 19 June 2008 / Page 1/ 10.1126/science.1157707.

UNESCO-SCOPE (2006). http://unesdoc.unesco.org/images/0015/001500/150010e.pdf.

Veron, J.E.N., 2008. Mass extinctions and ocean acidification: biological constraints on geological dilemmas. Coral Reefs 27, 459-472.

Ward, P. D., 1994. The End of Evolution: On Mass Extinctions and the Preservation of Biodiversity. Bantam, New York.

Ward, P., 2007. Under a Green Sky: Global Warming, the Mass Extinctions of the Past, and What They Can Tell Us About Our Future. HarperCollins, NY, 135 pp.

Zachos, J., Pagani, M.N., Sloan, L., Thomas, E., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686-693.

Zachos, J.C, Dickens, G.R.; Zeebe, R.E., 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451 (7176): 279–83.