Feature

Homo Sapiens on thin ice

By Andrew Glikson*

Humans have been shaped by survival through harsh glacial-interglacial climate cycles, culminating in the relatively stable conditions of the Holocene, which allowed Neolithic cultivation and civilization. Lately, the roles have been reversed. Natural global warming events, triggered by solar irradiation peaks and amplified by the release of water vapor, CO_2, CH_4 and nitrous-oxides from surface biomass, are magnified by the excavation and combustion of hundreds of billions of tonnes of carbon produced by over 400 million years of biological activity. Consequent greenhouse gas emission rates exceed those of the last glacial termination by orders of magnitude. Present growth rates of atmospheric greenhouse gas levels (2000-2005 - CO_2 +1.8-2.1 ppm/year) are tracking at the top end of the 1.5-5.6°C twenty-first century projections of the third Assessment report of the Intergovernmental Panel on Climate Change (IPCC). Sea level rise rates lag behind rising temperatures by about 10–30 years. The Australian continent, located between the southward-contracting Antarctic wind vortex and the equatorial El-Nino, is at the forefront of dangerous climate change, inducing droughts, fires and potential flooding of coastal population centres. Humans have the ingenuity and possess the technology to mitigate climate change and protect the biosphere from its severe consequences.

When land plants, represented by *Cooksonia, a* small naked plant bearing terminal sporangia, emerged on the continents some 425 million years ago, a fundamental change was heralded in the climatic evolution of planet Earth. The progressive build-up on land of an exposed combustible carbon-rich layer, and its buried equivalents, created potential tinderbox-like conditions, where solar irradiation maxima and fires caused by lightning trigger release of CO_2, CH_4, water, nitrous oxides and other greenhouse gases. By contrast, volcanic eruptions and asteroid impacts result in mixed atmospheric effects, including heating by released greenhouse gases and increased albedo and cooling due to ejected dust and sulphur aerosols.

Associated with the Permian-Triassic (251 Ma) and the Cretaceous-Tertiary (65 Ma) mass extinctions are telltale carbon isotope signatures, including an initial rise followed by a sharp decline in the heavy/light carbon isotopic ratio ($_^{13}C$). This drop-off represents the demise of biological activity followed by accumulation of biogenic debris, the so-called *graveyard shift*. An extinction event at the 54 Ma-old Paleocene-Eocene thermal maximum (PETM) is attributed to a major greenhouse event triggered by release from sediments of methane hydrates, with atmospheric levels of CO_2 reaching 900 ppm, raising high-latitude deep-ocean temperatures by c.5-7°C and mid-latitude terrestrial temperatures by c.4-5°C [1].

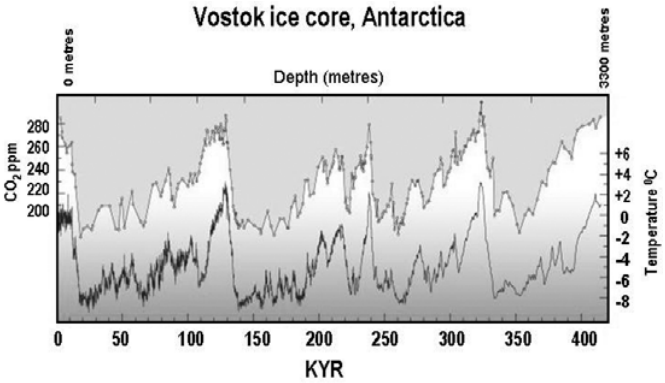

Figure 1. Variations in atmospheric CO_2 and air temperature determined from the Vostok (Antarctica) ice-core (after Petit *et al*., 1999 [2]). Note the sawtooth-like pattern, which signifies abrupt onset of warming periods, amplified by rapid increases in greenhouse gases.

Glacial-interglacial cycles recorded in marine sediments and ice cores as old as 740 kyr (1 kyr = 1000 years) are marked by sharp asymmetric isotopic $_^{18}0$ temperature records and parallel atmospheric CO_2 and CH_4 anomalies (Figs 1-3) [2]. The sawtooth-like patterns of these records imply sharp glacial terminations and rapid global-warming events, triggered by solar irradiation peaks related to cyclic orbital tilt and precession positions (~95-135 kyr, ~40 kyr, 20-26 kyr Milankovic cycles), amplified by feedback effects of greenhouse gases emitted from warming oceans, drying biomass and melting permafrost, and by reduced albedo due to melting of ice-covered areas. Thus, Petit *et al*. [2] state: "... the same sequence of climate forcing operated during each termination: orbital forcing (with a possible contribution of local insolation changes) followed by two strong amplifiers, greenhouse gases acting first, then deglaciation and ice-albedo feedback".

Minimum temperatures at the peak of the last glacial (c.19 kyr ago) were terminated by accelerated warming, reaching a relatively stable Holocene plateau (*Neolithic optimum*) c.10 kyr (Figs 2, 3), whereas sea levels continued to rise until 7 kyr by another 36 metres (Table 1). High temperature peaks c.14.5 kyr (*Older Dryas*) and c.11.5 kyr (*Youngest Dryas*) were accompanied by elevated greenhouse gas levels (Fig. 3). These peaks, associated with melting of the Laurentian and Greenland ice caps, releasing cold ice-melt currents, are represented by glacial debris, the so-called Heinrich events [3]. Retardation of the mid-Atlantic thermohaline circulation (Gulf Stream) resulted in freezing conditions in Europe. Sea levels between 15 - 7 kyr rose by about 100 metres, namely by a mean rate of 1.0-1.2 cm/year, at times accelerated to much higher rates [8] (Table 1).

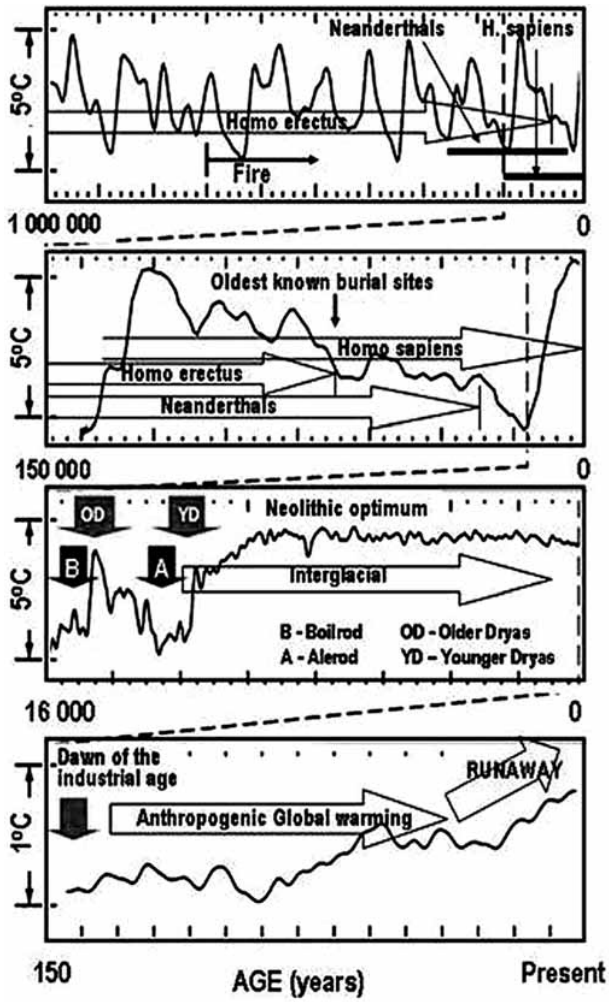

Figure 2. Generalised temperature variation plots for the last 1 million years (after Salzman, 2002[12]). Indicated stages in the development of hominoids added by the author.

Alternations between forests and grasslands, controlled by glacial-interglacial cycles, saw the descent of bipeds (*Australopithecus*) from the trees (c.5-3 Ma), later forcing the migration of *Homo erectus* (from about 1.9 Ma) through Africa, Europe and Asia (Fig. 2), using Aldovan stone tools. About 700 kyr, the mastering of fire heralded a quantum leap for *Homo erectus*, possibly the emergence of consciousness, later manifested at c. 75 kyr by burial and by ornaments. By 32 kyr, prior to the glacial peak at c.19 kyr, the Neanderthals did not survive the progressive freezing of Europe, leaving *Homo sapiens* with its Acheulian stone tools as the dominant species (Fig. 2). The relative climatic stability of the Holocene, with seasonal melt of mountain glaciers feeding river irrigation and cultivation, created the condition for the emergence of civilization in the fertile valleys of the Middle East and China. According to William Ruddiman, Neolithic forest clearing and agriculture, with consequent increase in greenhouse gases, prolong the Holocene, defined as the *Anthropocene.* There may even be hints extensive

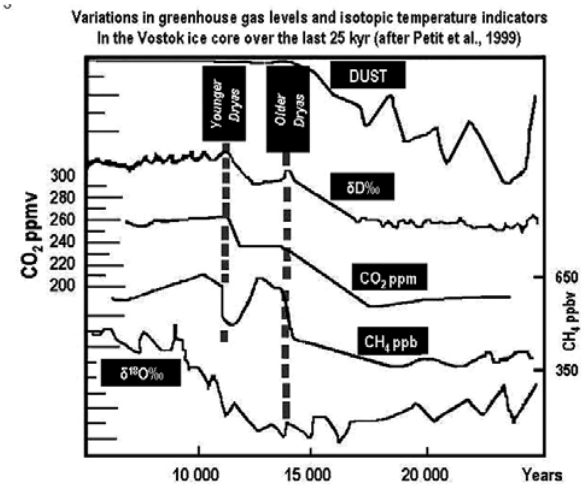

Figure 3. Variations in dust, _D‰ (deuterium), CO2, CH4, _18O‰ for the last 30,000 years recorded in the Vostok ice core (after Petit *et al*., 1999 [2]). Age resolution is in the order of several 10^2 years.

human-lit forest fires may have accentuated interglacial peaks as far back as 420,000 years(?) (Figs 1, 2)

Since the onset of the industrial era in the mid-19th century, the combustion of over 300 billion tonnes of carbon, from under 1 billion tonnes carbon/year before 1910 to nearly 6.5 billion tonnes carbon/year in 2000, mean CO_2 levels have increased from c. 280 ppm to 381 ppm (2005) (Table 1; Fig. 4). About half remains in the atmosphere at residence times of c.5 to 200 year, and half is absorbed equally by land and oceans. Since 1880 Mean temperatures have risen by about +0.8°C (mean land-sea temperature) (Fig. 5). Other increases include CH_4 (c.750-1620 ppb) with atmospheric residence time of c.12 years, nitrous oxides (270-314 ppb), chlorofluorocarbon vapors and ozone—resulting in an increase in radiative forcing by more than 2.15 Watt/m^2 (Fig. 4). Higher temperatures, droughts and fires result in a decrease in the CO_2 absorbing capacity of the ocean and biomass.

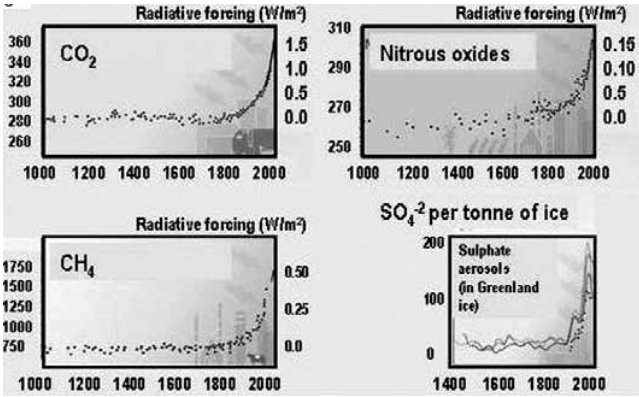

Figure 4. Atmospheric CO_2, CH_4, nitric oxide and sulphate aerosols changes during the second millennium (Intergovernmental Panel on Climate Change - IPCC-2001).

Warming by the greenhouse effect is superposed on the ~11 year-long sun spot cycle, which affects variations of about ±1.5 Watt/m². Until about the mid-1970s solar irradiation and temperatures were well correlated [9], but from that time temperature records rose by some 0.6°C [10]. Since about 2002 the greenhouse effect is manifested by continued increase in mean global temperature (Fig. 5), despite a decline in solar irradiance of ~1.0 Watt/m² [9, 10].

As documented in recent climate change reports [4], from about the mid-1970s global temperature rises accelerate due to reinforced infrared scatter effects (Fig. 4), amplified by land clearing, droughts, fires, thawing permafrost, decreasing reflectance (albedo) by melting glacials, and heating of ice-free water, causing high-latitude to polar regions to warm faster than low-latitude regions. Acidification of oceans (pH decrease by -0.1) affects carbonate-secreting organisms, placing the food chain under stress and further reducing CO_2 absorbing capacity. Rising sea levels (Table 1) erode the base of ice shelves, particularly in west Antarctica, allowing glaciers access to the seas.

A summary of mean variation rates of temperature, sea level and greenhouse gas concentrations based on ice core studies [2], IPCC-2001 [4], NASA-GISS [10, 11], CSIRO Marine and Atmospheric Research [7] is given in Table 1. Major trends include: (1) Rates of temperature rise from the mid-19th century are higher than those of the glacial termination (19 - 10 kyr) by more than a factor of 10, increasing to a factor of 20 from the mid-1970s. (2) Rates of sea level rise from the early 20th century (~0.2 cm/yr) were about twenty percent the glacial termination rate (~1.0-1.2 cm/year), accelerating to between +0.29 and 0.33 cm/year during 1993 - 2005. C. Rates of CO_2 increase from the late 19th century (~0.6 ppm/yr) are almost a factor of 50 the glacial termination rates (~0.014 ppm/yr), accelerating during 2000 - 2005 from 1.8 to 2.1 ppm/year. (3) Rates of CH_4 increase (~7 ppb/year) rose by a factor near 150 but appear to have somewhat stabilised late in the

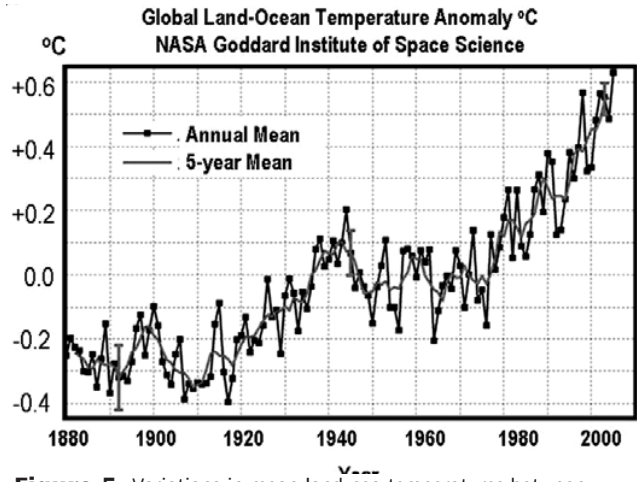

Figure 5. Variations in mean land-sea temperatures between 1880 and 2005 (Goddard Institute of Space Science) [10, 11].

Table 1. Temporal trends of temperature, atmospheric CO_2 and CH_4 levels, and sea level during the glacial termination (A), Holocene to 19th century (B), industrial age (C) and post 1970s (D) read from data records [References 2, 4, 6, 7, 8, 10, 11]

	Temperature anomaly °C	Sea level (metres) and change rates (cm/yr)	CO_2 ppm and change rates	CH_4 ppb and change rates
A)	19-10kyr +0.0009°C/yr 19-11 kyr +9°C +0.001°C/yr	17-11 kyr -120 to –60 metres +1.0 cm/yr	17-11.5 kyr 180-260 ppm +0.014 ppm/yr	17-11.5 kyr 370-630 ppb + 0.047 ppb/yr
(B)	Mostly stable 0-1100AD +0.00027°C/yr 1100-1600 -0.0012°C/yr -120 to –60 metres (LIA) [4] 1600-1900 +0.0013°C/yr	11-7 kyr -40 to –4 metres +1.2 cm/yr 7 kyr-1860: +4 m 0.057 cm/yr	11.5 kyr-19th century 265-255 ppm stable/decline	11.5 kyr-19th century decline
(C)	1880-1910 overall decline 1910-1945 +0.013°C/yr 1945-1980 fluctuates	1880-1965(5) +0.07 cm/yr 1904-1953 +0.203 ± 0.035cm/yr 1910-1990 +0.075 cm/yr 1920-1980 +0.25cm/yr 1965-1978(5) +0.2 cm/yr 1954-2003 +0.145 ± 0.034 cm/y	1800-2000 280-360 ppb (1.5 W/m¹) +0.66 ppm/yr	1800-2000 750-1620 ppb (0.5 W/m²) +7.25 ppb/yr
(D)	1975-2004 +0.019	1993-2004 +0.29 to +0.33 cm/yr	2000-2005 +1.8-2.1 ppm/yr 2006: 381 ppm	?stable

20th century. (4) Sea level rise rate peaks tend to lag about 10 - 30 years behind rising temperatures; thus, the accelerated rise of temperature and greenhouse gas concentrations from the mid-1970s is followed by accelerated sea level rise from about 1993. The observations suggest close links between temperatures and the rise of greenhouse gases, with the lag in sea level rise likely reflecting the delay factor in the melting of ice caps and glaciers.

Australia is located between major weather systems affected by climate change. To the south, the cold humid westerlies are migrating toward the ocean due to contraction of the Antarctic wind vortex (cover image). To the northeast, the *El Nino*-induced Pacific eastward warm flow reduces tropical rain in northeastern and eastern Australia, India and Africa. During 1950-2002 a decrease in seasonal precipitation to evaporation ratios (P/E) [5] resulted from combined global warming, land clearing and drying vegetation, with negative effects on rainfall. These changes affect the southern wheat belts, including south-western Western Australia (P/E -6 mm/year) and eastern coastal regions (P/E -6 to -8 mm/year). By contrast, monsoonal rains in northwestern Australia have gained by up to +6 mm/year.

Melting of the Greenland and west Antarctica ice sheets would raise sea levels by 6.5 and 7.3 metre, respectively. The rapid collapse and movement rates of west Antarctic and Greenland ice sheets, associated with penetration of surface water into their base, casts doubt on the IPCC-2001 estimated sea level rise of 0.88 metres to end-21st century.

Is there a tipping point? Humans possess the ingenuity and the technology to mitigate climate change and protect the biosphere from its severe consequences. Barring last-resort attempts at stratospheric aerosol injections (Crutzen, 2006 [13]), atmospheric CO_2 capturing utilities or iron-fertilization of oceans, efforts need to include sharp reduction of greenhouse gas emissions, fast-tracking of clean energy (clean coal, solar-thermal, geothermal, wind, hydrogen) technologies, solar-powered water desalination, wind-condensation channels, water treatment plants, continent-wide re-vegetation campaigns, long-range water conduits, drip irrigation systems and other measures. The human race will need to focus its resources and efforts to save the biosphere of the planet on which its future and that of other species solely depends.

To do otherwise will constitute a failure of the imagination.

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REFERENCES

1] Zachos, J.C. *et al*., 2001, Science, 292:686-693; Wing, S.L., *et al*., 2005, Science, 310:993-996; Thomas, D.J., 2002, Geology, 30:1067-1070; Ward, P., 2006, Sci. Am. October, 2006
[2] Petit *et al*., 1999, Nature, 399:429-436; Segenthaler, U. *et al*., Science, 310:1313-1317; Kump, L.R., 2002, Nature, 419:188-190; EPICA, 2004. Nature, 429:623-628
[3] Heinrich, H., 1988, Quaternary Geology, 29:142-152
[4] Intergovernmental Panel on Climate Change Third Assessment Report, 2001; Pittock, B.A., 2006, Climate Change: Turning Up the Heat. CSIRO Publishing; Steffen, W., 2006, Stronger Evidence but New Challenges: Climate Change Science 2001-2005, Aust. Greenhouse Office. Hansen, J., *et al*., 2006, Global temperature change, Proceedings of the National Academy of Sciences, 26 September:14288-14293;
[5] Dai, A. *et al*., 2005, AMS 16th Symp. Climate Change, San Diego, USA, 1-10
[6] Raupach, M., CSIRO Press Release, 27/11/06, http://www.csiro.au/csiro/ content/standard/ps2im.html; [7] Pittock, B.A., 2006, Human-induced climate change in a risk-management framework, Unpublished Report to the Govt Backbench Committee on the Environment and Heritage
[8] Liu, J.P. *et al*., 2004, Marine Geology, 209: 45-67
[9] Solanki, S.K., Fligge, M., 1998, Geophys. Res. Lett. 25:341-344; Solanki, S. K, 2002, Astronomy & Geophysics 43.5 doi: 10.1046/.1468-4004.2002.43509; Bard, E. and Frank, M., 2006., Earth Planet. Sci. Lett., 248:1-14
[10, 11] National Climatic Data Centre (NESDIS/NOAA) and Goddard Institute of Space Studies
http://www.ncdc.noaa.gov/oa/climate/research/2005/ann/ann05.html http://www.cmdl.noaa.gov/aggi/
[12] Salzman, B., 2002, Dynamical Paleoclimatology, Intern. Geophys. Ser. 80, 354 pp. San Diego: Harcourt–Academic Press)
[13] Crutzen, P., 2006, Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? Climate Change, 77:211-220.