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EDITORIAL

Carbon Dioxide, Climate Change and Geoengineering

Carbon dioxide (CO_2) is a deceptively simple molecule. It is encountered in early chemistry courses, when molecular shapes are introduced for the first time. Teachers hold up CO_2 as an example of a molecule in which the three constituent atoms lie on a straight line; a 'linear' molecule as opposed to the 'bent' structure observed in the other common triatomic molecule, water (H_2O). In biochemistry, CO_2 appears as a product of animal respiration and a substrate for photosynthesis carried out by plants, a process in which the carbon in CO_2 is 'fixed' by conversion to glucose. There is a remarkable economy, a more appropriate word may be sustainability, in biology. Animals and plants coexist in a symbiotic relationship; a bond of cooperation and coexistence imposed by chemistry and biology. In geology, CO_2 provides an entry to geochemistry through the study of limestones and carbonates in water. To the spectroscopist, CO_2 appears at an early stage in discussions of normal modes of vibration, which absorb infrared radiation. I have encountered CO_2 in many discussions of molecular shape, spectroscopy and photosynthesis for much of my scientific career, but have scarcely thought of CO_2 as a molecule which would one day occupy the attention of the world's politicians; a molecule that today stands charged with, almost singlehandedly, being responsible for global warming and climate change. In retrospect, the problem seems obvious. Almost all human activity is powered by the burning of fossil fuels, a process which oxidizes organic carbon to CO_2, leading eventually to rising levels in the atmosphere. Diminishing forest cover, an inevitable consequence of development, reduces CO_2 absorption. As atmospheric CO_2 concentrations rise, heat radiated from the earth is trapped, leading to the phenomenon described by a phrase, which now rolls off the lips of every public figure with a familiar ring – 'global warming'. As the Earth's atmosphere warms up, glaciers and polar icecaps must melt, oceans and snow-fed rivers must rise, low lying areas must go under water and as always, the hardest hit will be the populations of the poorer countries. The rise of global temperatures must inevitably affect the dynamics of the atmosphere giving rise to 'climate change', another term that has entered the vocabulary of all educated persons. Hollywood movies have now replaced visions of a world rendered desolate after a nuclear war, by images of cities trapped in a new ice age. The area of climate change has now grown into an industry; international conferences abound, held most often in exotic locations; treaties and protocols are promoted by some countries, rejected by others; Nobel Peace Prizes are awarded to the most visible campaigners in the battle to control global warming; and the scientific literature is beginning to see the emergence of a new discipline termed 'geoengineering', based entirely on simulations. Global warming, climate change, geoengineering, carbon trading and carbon footprints are terms that are part of today's dictionary; their origins trace back to the chemistry and biology of CO_2.

There is a famous graph that is shown in almost every lecture on climate change, which summarizes the variation of atmospheric carbon dioxide as a function of time, beginning with measurements made in the late 1950s. Why was CO_2 in the atmosphere measured, with precision, at a time when the term 'nuclear winter' was becoming common and 'global warming' was not yet conceived? The first measurements were made by Charles Keeling, working as a postdoctoral fellow at Caltech in the mid-1950s. Keeling died in 2005. In an extremely readable prefatory chapter entitled 'Rewards and penalties of monitoring the earth' (*Annu. Rev. Energy Environ.*, 1998, **23**, 25), Keeling traces his interest in the problem to a suggestion by his mentor Harrison Brown on the power of applying chemical principles to geology. In Keeling's words: 'He suggested that the amount of carbonate in surface water and near-surface ground water might be estimated by assuming the water to be in chemical equilibrium with both limestone and atmospheric carbon dioxide'. Keeling had found a project that linked chemistry and geology, which was to turn into a lifetime's work. Keeling's description of his effort to build an apparatus to measure CO_2 concentrations in air evokes memories of an era where successful experimental design always had the stamp of simplicity. He used a gas manometer based on a 1916 design and 'a dozen 5-liter glass flasks. . . each closed off with a stopcock to hold a good vacuum'. Having struggled with failed vacuum and leaky stopcocks in my youth, I was riveted by Keeling's account. Keeling soon discovered that measurements in Pasadena were irreproducible, variations being a consequence of immediate human activity. He travelled to Big Sur in California to sample 'the pristine air next to the Pacific Ocean', developing an elaborate sampling strategy. Keeling reflects, decades later, that his strategy was probably not required. Why then did he do it? His answer is engaging: 'The reason was simply that I was having fun. I liked designing and assembling equipment. I didn't feel under any pressure to produce a final result in a short time. It didn't occur to me that my activities and progress might soon have to be justified to the sponsoring Atomic Energy Commission'. Reading Keeling's account, I could not but marvel at the fact that enjoyment was the catalyst that triggered an experiment, whose results are the basis of all climate change discussions today. Keeling acknowledges that there are skeptics who do not believe there is a global warming problem; he adds that 'there are some who doubt that atmospheric CO_2 concentrations are rising'. There is little cause now to worry about the accuracy of CO_2 data; the work of Keeling and others has established these measurements on a firm footing. He notes that 'there is greater justification to doubt that air temperatures are rising' but argues that 'the atmospheric CO_2 record makes any other interpretation difficult'. The consensus today is that climate change is already upon us, requiring a serious strategy for limiting the use of fossil fuel in order to limit CO_2 emission. This is an area where the results of science have a direct and immediate impact on discussions of public policy.

The climate change debate has attracted authors and film makers. Michael Crichton's book *State of Fear*, a laboured work of fiction, is an attack on climate science research and its practitioners. Unlike *Jurassic Park*, it does not really stimulate the imagination. At the other end of the spectrum is the movie *An Inconvenient Truth*, that has the former US Vice-President Al Gore in a professorial role, lecturing on the need to arrest climate change. For the environmental activists, climate change is a new cause; an issue discussed provocatively by Freeman Dyson in the *New York Review of Books* (2008, **55**, June 12). Dyson's review focuses on two books that address issues of global policy and economics; discussions which can be disturbing and dismal when centred on 'carbon prices' and market rates for generating CO_2 emissions. For the common person these discussions appear to point towards a 'pay and pollute' policy. At the end of his review, Dyson notes that 'the main point is religious rather than scientific. There is a worldwide secular religion which we may call environmentalism. . . The ethics of environmentalism are being taught to children in kindergartens, schools and colleges all over the world. Environmentalism has replaced socialism as the leading secular religion. And the ethics of environmentalism are fundamentally sound. Environmentalism, as a religion of hope and respect for nature is here to stay. This is a religion that we all share, whether or not we believe that global warming is harmful'.

Is there a 'technological fix' to retard global warming and climate change? The emergence of a new term in the scientific literature, 'geoengineering' suggests that there will soon be a sizable group of scientists suggesting imaginative (and possibly dangerous) ways of 'engineering climate'. One of the approaches that appears to be gaining attention, largely thanks to an article by the Nobel laureate Paul Crutzen (*Climatic Change*, 2006, **77**, 211), is to develop strategies to reduce the amount of solar radiation reaching Earth. Crutzen suggested 'stratospheric sulfur injections', a process by which sulfur dioxide (SO_2) is let loose in the upper atmosphere, where a significant amount 'is converted to submicrometer size sulfate particles' which then contribute to 'backscattering to space of solar radiation'. Other proposals including 'orbiting sunshades' have appeared (Robock, A., *Science*, 2008, **320**, 1166). Geoengineering appears to be a fertile field for computer simulations (Matthews, H. D. and Caldeira, K., *Proc. Natl. Acad. Sci. USA*, 2007, **104**, 9949; Bala, G. *et al.*, *ibid*, 2008, **105**, 7664), driven by 'the desire to have the benefits of abundant fossil fuel energy without unfortunate consequences' (Brewer, P. G., *Proc. Natl. Acad. Sci. USA*, 2007, **104**, 9915). Is 'engineering' an appropriate descriptor for proposals to modify climate by geochemical and geophysical approaches? In an article highlighting the area of geoengineering entitled, 'Climate change: Is this what is takes to save the world?', there is an interesting thought: 'Humanity has shown a great capacity to make a mess, mostly as a side effect of just trying to make a living. But that is not engineering. Engineering involves intention' (Morton, O., *Nature*, 2007, **447**, 132). The Human Development Report 2007/2008 (UNDP) is subtitled 'Fighting climate change: Human solidarity in a divided world'. The report is exhaustive and well produced. Curiously, the chapter entitled 'Avoiding dangerous climate change: Strategies for mitigation' begins with a quote attributed to Mahatma Gandhi: 'Speed is irrelevant if you are going in the wrong direction'. In casually reading about climate change and some of the underlying science, I was left marvelling at how far we have travelled from Keeling's five liter flasks and precise measurements of CO_2 in the air to a world where economists and politicians can use carbon dioxide as a new currency in international relations.

P. Balaram