The greenhouse effect

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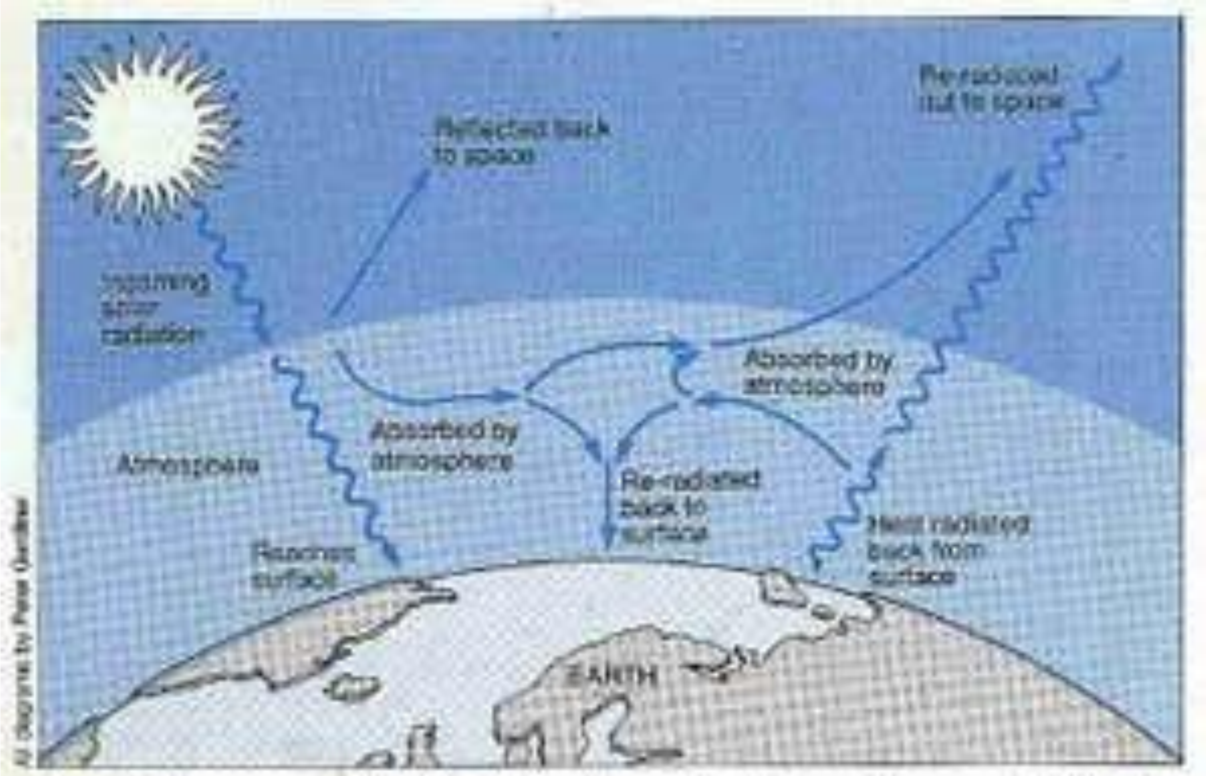
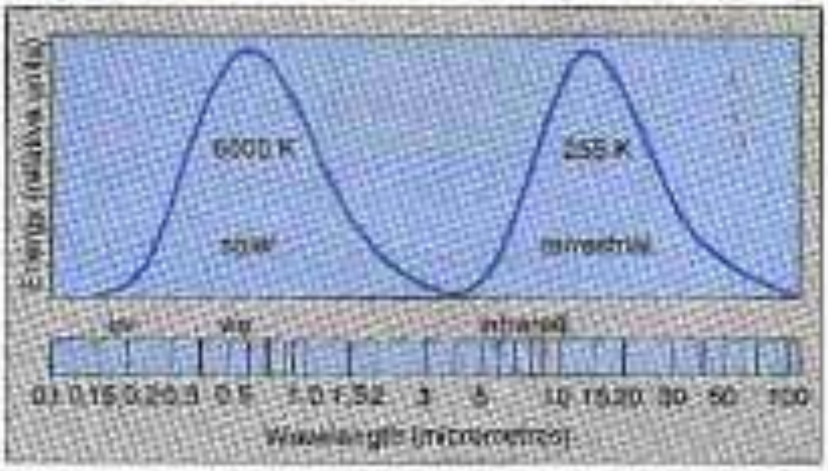
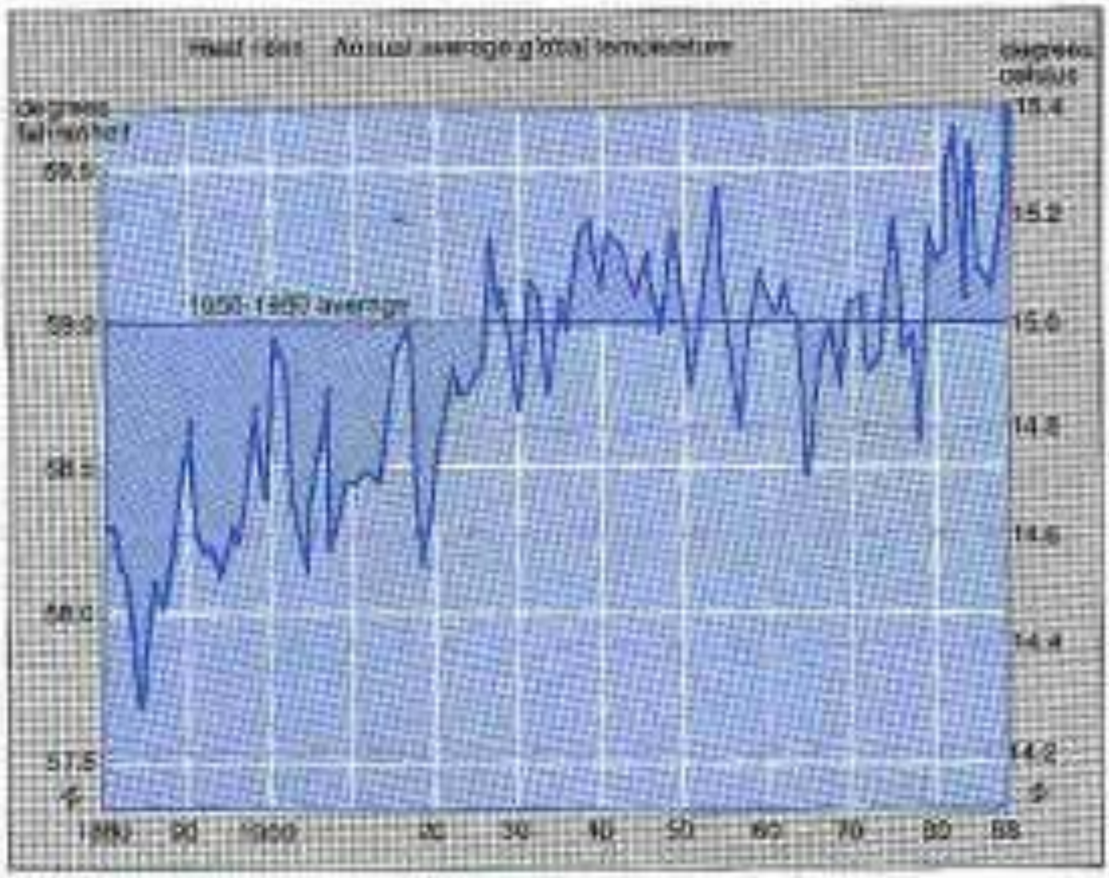


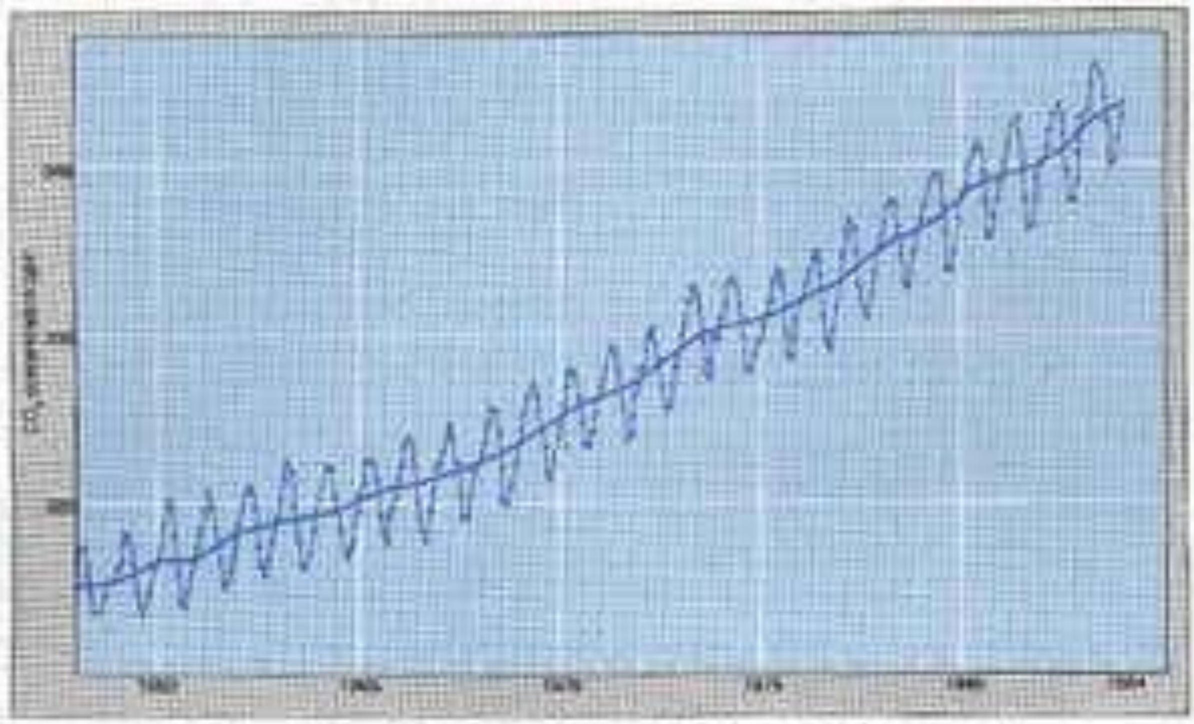
Some of the energy radiated at infrared wavelengths from the ground is absorbed and re-radiated downwards by the atmosphere—the greenhouse effect



The same amount of energy that the Earth receives from the Sun is radiated back into space, but at longer wavelengths

Annual average temperatures since 1880. (Source: J. E. Hansen and S. Lebedeff.)





The build-up of carbon dioxide in the air, recorded at Mauna Loa Observatory, Hawaii

Any change in the weather these days seems to be blamed on warming of the world caused by human activities – the “greenhouse effect”. But although human activities may be upsetting a natural balance, the greenhouse effect is very much a natural feature of the world, and without it we would not be here

THE EARTH is comfortably warm because it is surrounded by a blanket of air. “Comfortably warm” means that the average temperatures on our globe are in the range between 0°Celsius and 100°Celsius where water is liquid. We can see that the atmosphere of the Earth has something to do with this by comparing the temperatures with which we are familiar with those on the surface of the Moon. The Moon is an airless “planet” which is almost exactly the same distance from the Sun – the ultimate source of heat in our Solar System – as we are. On the airless Moon, the temperature rises to 100°C on the sunlit surface, and falls to -150°C at night.

The surface temperature of the Moon averages about -18°C. At this temperature, the energy radiated from the Moon’s surface into space just balances the incoming heat from the Sun. If the Earth had no blanket of air and was a bare, rocky ball like the Moon, it would also have an average temperature of about -18°C. In fact, the average temperature of our planet in the layer of air just above the surface is about 15°C. The blanket of air keeps our planet some 33°C warmer than it would otherwise be.

How does it achieve this? Solar energy is radiated chiefly in the visible part of the spectrum, in a band from 0.4 to 0.7 micrometres. This radiation, and short-wave infrared, passes through the atmosphere of the Earth without being absorbed – although some of it is reflected back into space by clouds – and warms the surface of the land or sea. About 7 per cent of the Sun’s energy is radiated at shorter wavelengths, below 0.4 micrometres, in the ultraviolet; this is important in maintaining a layer of ozone in the stratosphere (see Inside Science Number 9). At the other end of the spectrum, above 0.7 micrometres, energy is radiated in the infrared. This infrared energy is exactly the same as the radiant heat you feel when you warm your hands in front of a hot household radiator.

Incoming solar radiation

A blanket for the Earth

THE wavelengths at which a hot object radiates most energy depend on the temperature of the hot object. The Sun has a surface temperature of about 6000°C, and this corresponds to radiation in the visible band. The surface of the Earth, warmed by solar radiation, has a temperature of a few tens of degrees Celsius, and therefore radiates in the infrared, chiefly in the range from 4 to 100 micrometres.

Water vapour absorbs strongly in the band from 4 to 7 micrometres, and carbon dioxide absorbs in the band from 13 to 19 micrometres. Between 7 and 13 micrometres there is a “window” through which more than 70 per cent of the radiation from the Earth’s surface ultimately escapes into space.

Because of the absorption, infrared heat radiated by the warm surface of the planet cannot escape freely into space, and warms the lower layer of the atmosphere – the troposphere. Because the air in the troposphere is warm, it radiates heat in turn, still at infrared wavelengths. Some of this heat goes back towards the ground, and keeps it warmer than it would otherwise be – the greenhouse effect.

As long as the amount of water vapour and carbon dioxide in the air stays the same, and as long as the amount of heat arriving from the Sun is constant, an equilibrium is established. The “greenhouse gases” (carbon dioxide, water vapour and, as we shall see, one or two other gases) not only absorb but also emit infrared radiation. Because the temperature of the troposphere decreases with increasing height, the net effect is that each layer of the atmosphere absorbs energy radiated from below, at warmer levels, and passes it upwards, ultimately to escape into space at a lower temperature. The overall effect is to reduce the infrared radiated into space. The temperature at the surface must then rise until the amount of long-wave radiation leaving the Earth balances the amount of energy coming in from the Sun.

Both the ground and the air are warmed by the greenhouse effect. Present concern about the greenhouse effect began with the realisation that human activities are upsetting the natural balance by increasing the amount of carbon dioxide in the atmosphere. This strengthens the greenhouse effect. It is now also clear that other gases being released as a result of human activities – other “anthropogenic” gases – absorb infrared radiation in the window from 7 to 13 micrometres where radiation used to escape freely. The combined effects of these anthropogenic greenhouse gases are likely to warm the world significantly over the next few decades.

The carbon dioxide trap

An enriched atmosphere

SCIENTISTS have known about the greenhouse effect since the middle of the 19th century. A British scientist, John Tyndall, published a paper in the Philosophical Magazine in 1863 about the effect of water vapour as a greenhouse gas. In the 1890s, a Swede, Svante Arrhenius, and an American, P. C. Chamberlain, both considered the problems that might be caused by a buildup of carbon dioxide in the air, and therefore a global warming, caused by combustion of coal. Average surface air temperatures, worldwide, did indeed rise slightly in the early part of the 20th century, by about 0.25°C between 1880 and 1940. In the years following the US dustbowl of the 1930s, scientists suggested that this was a sign of the anthropogenic greenhouse effect at work. But between 1940 and 1970 the world cooled by about 0.2°C, and the possibility of an increased greenhouse warming of the globe was not a major subject of scientific research. The situation changed because measurements of the amount of carbon dioxide in the atmosphere began to show a significant increase, stimulating a wave of scientific activity in the 1970s and forecasts that a doubling of the 19th century "natural" concentration of carbon dioxide would cause the world to warm by about 2°C.

Between 1970 and 1980, just at the time these forecasts were being made, the world's mean temperature increased by about 0.3°C, and the rapid warming seems to have continued into the 1980s. Although records of temperature go back to only the 1850s, 1989 was the warmest year on record. There is no proof that this is solely, or even primarily, a result of the anthropogenic greenhouse effect. But it certainly gives research into the greenhouse effect a topical interest.

Accurate measurements of the amount of carbon dioxide in the air began to be taken at Mauna Loa (in Hawaii) and at the South Pole, in the International Geophysical Year, 1957-58. These measurements are an important guide because they are taken far away from any major sources of industrial pollution, and represent the "well-mixed" state of the atmosphere. They show a clear annual rhythm, associated with the seasonal changes in vegetation over the land masses of the Northern Hemisphere – the Earth's vegetation "breathes" carbon dioxide in and out over an annual cycle (this is dominated by the Northern Hemisphere because that is where most land lies). But by the 1970s it was also clear that this annual cycle is superimposed on a rising trend of global mean carbon dioxide concentration.

In 1957, the concentration of carbon dioxide in the atmosphere was 315 parts per million (ppm). It is now about 350 ppm (0.035 per cent). Most of the extra carbon comes from burning fossil fuel, especially coal; part of the increase may be due to the destruction of tropical forests.

When 1 tonne of carbon, perhaps in the form of coal, is burnt, it produces about 4 tonnes of carbon dioxide, as each carbon atom is combined with two atoms of oxygen from the air. By the early 1980s, some 5 gigatonnes (5 thousand million tonnes; 5 Gt) of fuel were being burnt each year, so the annual input of carbon dioxide to the atmosphere from combustion of fossil fuel had reached about 20 Gt. The increase in the carbon dioxide concentration of the atmosphere, however, corresponds to slightly less than half the amount of carbon dioxide produced by human activities each year. Roughly half the carbon dioxide we produce is absorbed in some natural sink (or sinks). Some may be taken up by vegetation, which grows more vigorously in an atmosphere enriched with carbon dioxide – "vegetation" here includes the biomass of the sea, dominated by micro-organisms such as plankton. Some may be dissolved in the oceans.

Between 1850 and 1950, roughly 60 Gt of carbon was burnt, chiefly as coal, in the burgeoning industrial revolution. As much carbon again is now being burnt every dozen years. The input of carbon dioxide to the atmosphere between now and the end of this century will probably be as great as the input in the hundred years from 1850 to 1950.

Researchers estimate that in the middle of the 19th century the natural concentration of carbon dioxide in the atmosphere was about 270 ppm. They have also measured, in bubbles of atmospheric gases which have been trapped in the polar ice sheets, similar concentrations of carbon dioxide from the period before industrialisation.

Calculations of the likely effect of the buildup of carbon dioxide in the atmosphere on climate are usually presented in terms of the increase compared with the background level of 270 ppm. Studies of air bubbles trapped in ice cores from the Antarctic show that roughly the same concentration of carbon dioxide persisted throughout the past 10 000 years.

Climatic changes

Hotter, wetter weather

DIFFERENT computer models of the global climate produce slightly different figures, but it is a reasonable rule of thumb that doubling the carbon dioxide concentration of the atmosphere from the baseline of 270 ppm will produce an increase in global mean temperatures of about 2°C. But this is less than half the story. The same computer models show that the warming is likely to be much greater at high lattitudes, near the poles, while the tropics, which are already hot, will warm only slightly. At the same time, there will be changes in prevailing winds and in the distribution of precipitation around the globe. One key forecast is that continental interiors will dry out as the greenhouse effect takes a grip.

Simply extrapolating the present increase suggests that doubling of the carbon dioxide concentration will occur in almost exactly a hundred years from now, in the 2080s. This takes no account of the ways in which the use of energy globally is likely to change over the next century; the matter is now the subject of eager debate. But we can use this figure to put the carbon dioxide "problem" into perspective alongside the greenhouse effect of other gases being released to the atmosphere.

Several other gases that are being released by human activities – such as ozone, methane, nitrous oxide and chlorofluorocarbons (CFCs) – absorb infrared radiation in the window from 7 to 13 micrometres. CFCs, best known as the chemicals responsible for the holes in the ozone layer over the Arctic and Antarctica (see Inside Science Number 9) are very efficient greenhouse gases. One molecule of either of the two most common CFCs has the same greenhouse warming effect as 10 000 molecules of carbon dioxide.

Methane, which at present has an atmospheric concentration of 1.7 ppm, is increasing at a rate of 1.2 per cent per year, probably because of the biological activity of bacteria in paddy fields, and also because of the release of natural gas from commercial oil and gas fields. Nitrous oxide is building up from a concentration of 0.3 ppm at a rate of 0.3 per cent a year as the use of nitrogen-based fertilisers increases. Ozone near the ground (in the troposphere) is increasing as a result of human activities.

Veerhabadrhan Ramanathan, of the University of Chicago, has converted the greenhouse effects of all these gases into carbon dioxide equivalents, and projected their growth forward to the year 2030. By then, he claims, these minor contributions will probably add up to as big an effect as that of the extra carbon dioxide produced by human activities. In effect, they will double the strength of the anthropogenic greenhouse effect. On this basis, the effective doubling of the background concentration of carbon dioxide will occur by about the year 2030, half a century sooner than if carbon dioxide alone were increasing.

Climatic conflict

Greenhouse v. Ice Age

HOW will this affect the weather of the world? Nobody can say exactly, but one way to get an idea of the direction in which things will change in different regions of the globe is to look at the difference in weather patterns for warm years and cold years during the present century. Researchers at the Climatic Research Unit, at the University of East Anglia, carried out just such a study. They used data from the 50-year interval 1925-74, and picked out the five warmest and five coldest years during that interval.

The team looked first at temperature records from around the Arctic, between 65°N and 80°N. This includes northern Norway, northern Sweden, much of Finland, Iceland, northern Canada, Alaska and northern Siberia. In this zone, the temperature difference between the warm and cold extremes is 1.6°C, but the temperature difference averaged over the whole Northern Hemisphere is only 0.6°C. Comparing only winters, the warm extreme was 1.8°C warmer at these latitudes, while in summer the temperature difference was only 0.7°C. Overall, there is a 1-2 per cent increase in rainfall in the warm years, which is expected since more water evaporates from the ocean when the world is warmer. But this modest average increase conceals much bigger regional effects, including a decrease in rainfall over much of the US, Europe, the USSR and Japan. India and the Middle East have greater than average increase in rainfall in this particular scenario.

This single study cannot be taken as a definitive guide to how weather patterns will change as the world warms, but it bears out the computer forecasts (suggesting that high latitudes warm three or four times more than average). It also indicates that the patterns we are all used to, and on which present agricultural practices are based, are unlikely to be "normal" in the years ahead.

In itself, the greenhouse effect is not necessarily a bad thing. It is almost certainly a more desirable state of the world, from the human point of view, than the onset of a new Ice Age might be. But what matters is the way human society responds to this environmental challenge. It is now certain that the world will change, as a result of the greenhouse effect, during the lives of all of us. Plans that are made on the basis of how things used to be – agricultural plans, design of flood barriers, calculations of the need for reservoirs of drinking water, and so on – will almost certainly be wrong. This is why climatologists now point to the example of the droughts which hit the US in 1988. Those droughts were not caused directly by the greenhouse effect. Although 1988 is the warmest year on record, 1987 was nearly as warm, and there were no comparable droughts then. But whatever the immediate cause of those droughts, they are an indication of the kind of shortages of rainfall that are likely to be increasingly common in the heart of North America, and other continental interiors, as we move into the 21st century.

The greenhouse effect should be a factor in all long-term planning, and it impinges directly on politically contentious issues such as the choice between nuclear and fossil fuel for future generations of power stations. Ironically, in this context it is nuclear power that is the environmentally clean alternative. That example highlights the difficulty of coming to grips with the greenhouse effect.

Rising sea levels and melting ice caps

THE OTHER immediate effect of an increase in global mean temperatures is a rise in sea level. This is already happening. Sea level has risen by about 15 centimetres during the 20th century, and the rise is very much in line with the rise in temperature that has occurred over the same interval. Most of this rise can be explained simply in terms of the thermal expansion of sea water. Only a little extra water has been added to the sea, by melting glaciers on mountains at low latitudes. Paradoxical though it may seem, at present the polar ice caps may be increasing in size. This is because more moisture is evaporating at low latitudes, and this is falling as snow near the poles, where it is still cold. A global warming of about 2°C, possible within 40 years, will increase sea level by a further 30 centimetres or so, largely because of the expansion of sea water.

But one "scare story" associated with the greenhouse effect is dismissed by the experts. This is the fear that the entire West Antarctic ice sheet might collapsesliding into the ocean and raising sea level worldwide. Some calculations do suggest that once the world warms by about 4°C (which could happen before the next hundred years is over) the ice sheet might "collapse". But what glaciologists mean by a collapse is still a slow process by everyday standards – it would take several hundred years for all the West Antarctic ice to slide into the sea, eventually raising sea levels by 5 metres or more, but only at a rate of one or two centimetres a year. There would be ample time to walk out of harm's way, although the impact on coastal cities and low-lying countries, such as Bangladesh and The Netherlands, would be catastrophic in the long term.

Further reading

The definitive study is The Greenhouse Effect, Climatic Change and Ecosystems, edited by Bert Bolin, Bo Döös, Jill Jäger and Richard Warrick (Wiley, Chichester). It is big and expensive, but worth investigating in a library. Hothouse Earth, by John Gribbin (Black Swan) puts the greenhouse effect into perspective against the history of global climate, and the New Scientist Guide The Breathing Planet (Blackwell) goes into a little more detail.