Climate Change

- a brief introduction for scientists and engineers
- or anyone else who has to do something about it

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Preface

Climate change has been written about at many levels, from popular articles in newspapers, to specialized research papers in the scientific literature. Here I present a short (~ 100 page) technical overview, meant for anyone who has to deal with the issues involved and who has studied a science subject at secondary school or higher level. Climate change covers the whole spread of the sciences, from the physics of the Sun to the biology of oceanic plankton. I hope this review will be useful as an introduction to anyone who needs the broad picture as a background to their particular concern, be they biologist, oceanographer, agronomist, engineer, or whatever.

Notes about references

References are given in parentheses, within the text. Books and articles for further reading are listed at the end of each chapter. References to reports published by the Intergovernmental Panel on Climate Change (IPCC) are abbreviated as follows.

IPCC, 2001: *Climate Change 2001: The Scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds)], Cambridge University Press, Cambridge, UK, 881pp. Abbreviated to IPCC, 2001: *Climate Change*. I.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds)], Cambridge University Press, Cambridge, UK, 996pp. Abbreviated to IPCC, 2007: *Climate Change*. I.

IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof , P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp. Abbreviated to IPCC, 2007: *Climate Change*. II.

IPCC, 2007: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, UK, 851pp. Abbreviated to IPCC, 2007: *Climate Change*. III.

Abbreviations used

AOGCM	Atmospheric-Ocean General Circulation Model
CCGT	Combined Cycle Gas Turbine
CCS	Carbon (dioxide) Capture and Storage
DIC	Dissolved Inorganic Carbon
GDP	Gross Domestic Product
GPP	Gross Primary Production
GWP	Global Warming Potential
IGCC	Integrated Gasification Combined Cycle (electricity generating plant)
IPCC	Intergovernmental Panel on Climate Change
NPP	Net Primary Production
OTEC	Ocean Thermal Energy Conversion
TFC	Total Final Consumption (of energy, by humans)
TPES	Total Primary Energy Supply (of energy, to humans)
TSI	Total Solar Irradiation
VOC	Volatile Organic Compound

Acknowledgements

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I also thank the following authors and organisations for permission to reproduce diagrams taken from their published work.

Figure 1.1. From C. Wehrli. 1985. *PMO/WRC, Publication No.615*, Physikalisch Meteorologisches Observatorium, Davos, Switzerland.
Figure 1.2. This is part of Figure 1 in M. Lockwood & C. Fröhlich. 2007. *Proc. Roy. Soc. A,* **463**, 2447-2460.
Figure 1.7. Part of Figure TS.20, Climate Change 2007: The Physical Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Figure 1.9 a & b. This is part of Figure 3 in J. Hansen, M. Soto, P. Kharecha, G. Russell, D.W. Lea & M. Siddalll. 2007. *Phil Trans R. Soc. A,* **365**, 1925-1954.
Figure 4.1. Part of Figure TS. 22, Climate Change 2007: The Physical Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Figure 4.2. Part of Figure SPM.5, Climate Change 2007: The Physical Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Figure 4.3. From Figure SMP.7, Climate Change 2007: The Physical Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Figure 5.2. From Figure TS.2b, Climate Change 2007: Mitigation of Climate Change. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Figure 10.1. Figure 1 from Prins et al. 2009: 'How to get climate policy back on course', Institute for Science, Innovation and Society, Oxford.

The remaining Figures are either original to this work, or taken from the public domain, with acknowledgement in the individual Figure Legends.

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Chapter 1 – the science of climate change

1.1 Solar radiation

The Earth receives virtually all its radiation energy from the Sun, some eight and a half minutes after this radiation leaves the solar surface. This energy ultimately comes from thermonuclear fusion deep inside the Sun, where helium is continuously being formed from hydrogen, with the mass lost during the reaction appearing as energy.

Total solar irradiance (TSI, also sometimes called the 'solar constant') is a convenient measure of the Sun's output for terrestrial purposes: it is the radiation received from the Sun, integrated over the whole spectrum, at the Earth's mean distance from the Sun, outside the Earth's atmosphere, measured in watts per square metre. **Figure 1.1** shows how solar energy is distributed across the spectrum, with about 48 % of the energy in the infra-red part of the electromagnetic spectrum, 44 % in the visible part and some 8 % in the ultra-violet.

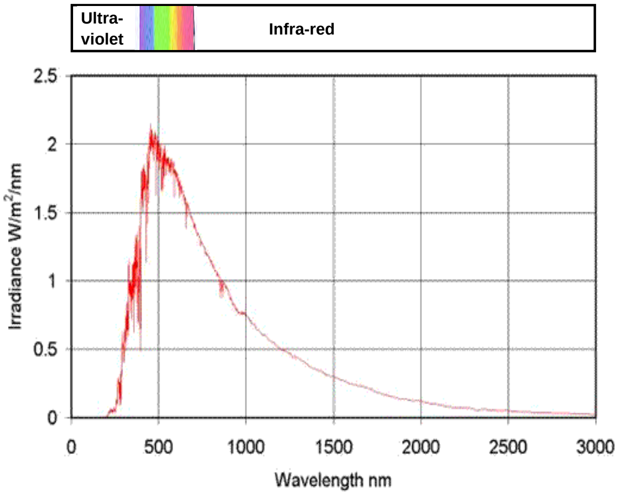

Figure 1.1 Extraterrestrial solar spectrum.

From Wehrli. 1985. *PMO/WRC, Publication No.615*, Davos, Switzerland. The visible part of the spectrum runs from about 400nm (violet) to about 700nm (red).

TSI measured by satellite is about 1366 Wm^{-2} , varying slightly in step with the eleven year sunspot cycle – see below. Thus, for the whole Earth, with a cross section of 1.274×10^8 km^2, the power is 1.740×10^{17} W, roughly ten thousand times the total power (1.52×10^{13} W, from coal, oil, gas, hydroelectricity, etc.) used by people in 2005. To put humans in their cosmic perspective, the whole Earth receives only 0.00000005 % of the energy radiated in all directions by the Sun. The radiation received by the Earth is determined by its cross section (πR^2), but as the planet rotates this energy is distributed across the entire surface area ($4 \pi R^2$). Hence the average incoming solar radiation,known as "insolation") is one fourth the TSI or ~342 Wm^{-2}. Again, this figure is for the *average* distance from the Earth to the Sun.

Cyclical changes in solar activity (linked with changes in sunspot number) alter the quantity of radiation that reaches the Earth (**Figure 1.2**). Thus the amount of solar radiation

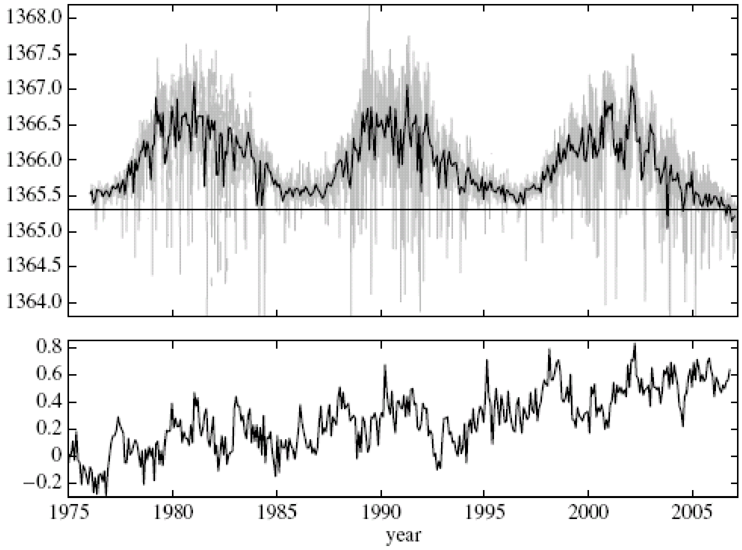

Figure 1.2 The upper diagram shows Total Solar Irradiance, in Wm^{-2}, over the last three solar cycles; the lower, global mean surface air temperature, in ^{o}C, as departure from the 1951-1980 mean.

From Figure 1 in Lockwood & Fröhlich. 2007. *Proc. Roy. Soc. A,* **463**, 2447-2460. The black lines in the upper diagram are monthly means and the daily values are in grey. It is worth noting the short-term fluctuations in both diagrams – these are entirely normal for anything to do with weather, but the bane of anyone trying to establish long-term trends.

received at the outer surface of the Earth's atmosphere varies by approximately 0.1% or about 1.3 Wm^{-2} from peak-to-trough of the 11 year sunspot cycle. However the claim that warming is caused, not by human activities, but by changes in solar activity, is untenable on present evidence. There is no direct link between TSI (upper part of **Figure 1.2**) and the dramatic increase in global air temperature over the last three decades (lower part of **Figure 1.2**). Nor is it possible to link changes in the cosmic ray flux reaching the Earth (see Svensmark & Friis-Christensen. 1997. *JASTP,* **59**, 1225-1232) to this rise in temperature (Lockwood & Frohlich. 2007. *Proc. Roy. Soc. A,* **463**, 2447-2460)**.**

1.2 The atmosphere

The lowest part of the atmosphere, where the weather occurs, is the troposphere – see **Figure 1.3**. The troposphere (from the Greek 'tropos', meaning mixed) contains about 80 % of the atmospheric mass and virtually all of the water, either as vapour or in clouds. It is thicker at the equator and thinner at the poles. The characteristic feature of the troposphere is that temperature decreases with height, from 14 ^{o}C at the surface (the mean global surface temperature), to a mean temperature of -58 ^{o}C at the tropopause, the upper edge of the troposphere. The mean fall is about 6.5 ^{o}C km^{-1}, sometimes called the lapse rate. Above the troposphere is the stratosphere, where the air is calmer and drier. Together, the troposphere and stratosphere contain 99.9 % of the atmospheric mass. In the stratosphere, temperature *increases* with height, from about -58 ^{o}C at its base to about 0 ^{o}C at its upper limit, which is called the stratopause. The stratosphere contains the 'ozone layer', which absorbs incoming solar ultra-violet radiation –see **Chapter 2.19**. The energy absorbed in the stratosphere is released at longer wavelengths in the infra-red and is the cause of the increase in temperature with height in this part of the atmosphere.

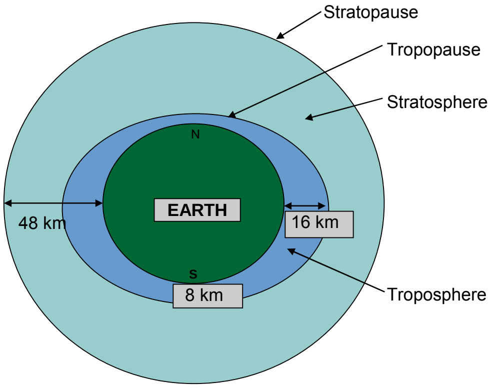

Figure 1.3.
The Earth's inner atmosphere

1.3 The greenhouse gases and absorption of radiation by the atmosphere

The major gases in the atmosphere – nitrogen (N_2, which accounts for 78 % by volume in dry air), oxygen (O_2, 21 %) and argon (Ar, 1 %), do not absorb in the visible or infra-red part of the spectrum. However several trace gases naturally present in the atmosphere, although almost completely transparent to visible light, do have the ability to absorb and emit radiation in the infra-red – i.e. they have absorption bands in this part of the spectrum. In order of importance, these 'greenhouse gases' are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), with ozone (O_3) occupying a variable position.

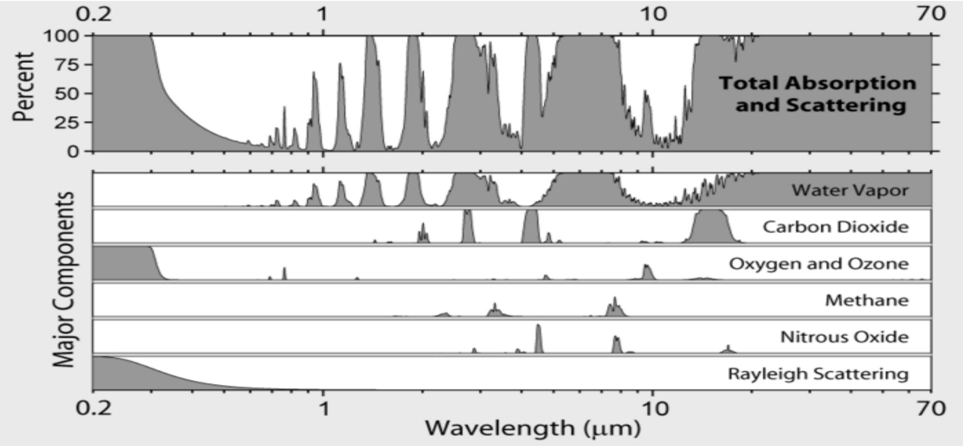

Figure 1.4 Atmospheric absorption bands in the near ultraviolet, visible and infra-red.

From: en.wikipedia.org/wiki.File:Atmospheric_Transmission.png . Note that this diagram shows absorbance – for example the atmosphere is opaque between 6 and 7 microns. The greenhouse gases, with their ability to interact with the radiation stream coming from the surface of the Earth, give rise to the greenhouse effect, which is described in detail in **Section 1.5**.

There has been confusion about the effect of increasing carbon dioxide concentration on the absorption of infra-red radiation by the atmosphere. A look (**Figure 1.4**) at the infra red absorption spectrum of moist air will illustrate the problem. In several parts of the spectrum transmittance is zero: no infra- red radiation gets through and the absorption is said to be 'saturated'. In regions where the absorption is saturated, a further increase in the concentration of the saturating gas has no effect. Carbon dioxide has a strong absorption band at 15 µm and at this wavelength the atmosphere is saturated: an increase in the atmospheric concentration caused by fossil fuel burning will have no effect on infra-red absorption by carbon dioxide at 15 µm. However carbon dioxide absorbs at many other wavelengths (including the shoulders of the 15 µm band), where the strengths of the bands are insufficient to absorb all the radiation and at these wavelengths an increase in concentration *will* cause an increase in absorption. Claims that increasing concentrations of carbon dioxide will not cause global warming because the absorption spectrum of carbon dioxide is already saturated are wrong (see IPCC, 2001: *Climate Change.* I, p. 93, for a detailed refutation).

Similar arguments apply to water vapour, which saturates much (but far from all) of the infra-red spectrum (**Figure 1.4**). In essence, changes in greenhouse gas concentrations are only relevant to global warming in regions of the absorption spectrum that are not saturated: i.e. to the infra-red 'windows' used by astronomers and microwave transmission engineers.

1.4 The radiation balance of the Earth

Under steady-state conditions, the energy received by the Earth in radiation from the Sun exactly balances that lost to space (**Figure 1.5**). Part of the incoming radiation is reflected by clouds and atmospheric aerosols, part reflected back from the surface of the Earth and the remainder absorbed by atmosphere, oceans and land. Radiation reflected by a surface has the same spectrum as the radiation reaching that surface: that absorbed by atmosphere, ocean and land is re-emitted at longer wavelengths, in the infra-red.

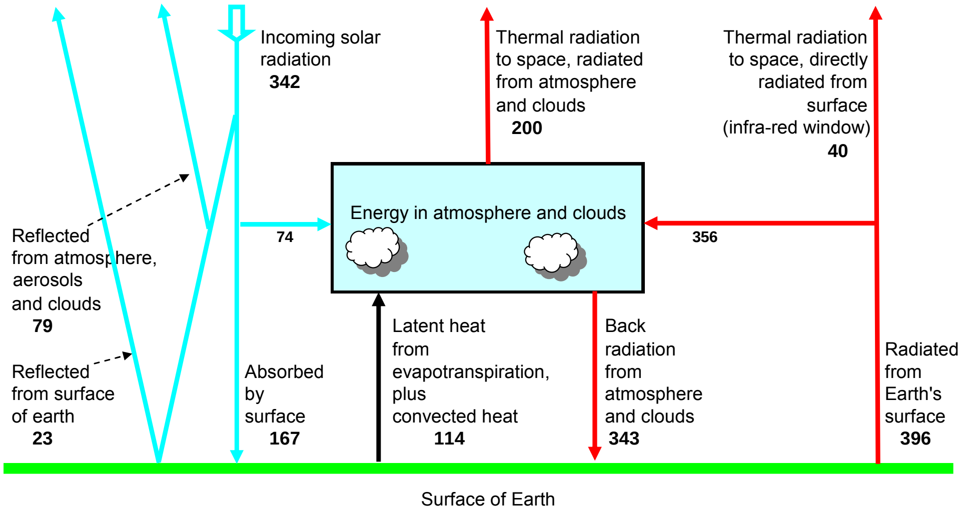

Figure 1.5 The global annual energy balance of the Earth.

Based on FAQ 1.1, Figure 1 in IPCC, 2007: Climate Change. I, updated by revised numbers from eosweb.larc.nasa.gov/PRODOCS/srb/table_srb.html. Incoming solar radiation in blue, emitted long wavelength radiation in red. The numbers are Wm^{-2}.

When there is a change in the system, for example a change in the radiation emitted by the Sun, the temperature of the Earth must then adjust (see **Section 1.6**) until the incoming and outgoing radiation energies at the top of the atmosphere are again in balance, as in **Figure 1.5.**

1.5 The greenhouse effect

Before considering how people influence the climate, it is necessary to examine the natural greenhouse effect. Any physical object radiates energy of an amount and at wavelengths typical for the temperature of that object. Thus a white-hot iron nail radiates more energy and at shorter wavelengths than the same nail when red-hot. Even when it has cooled to room temperature, it still emits radiation in the infra-red, but now at the same rate as it receives radiation from its surroundings. Because of its high temperature, most of the Sun's radiation is in the visible and ultra-violet parts of the spectrum (**Figure 1.1**), whereas virtually all of the radiation from the much cooler Earth is in the infra red. Greenhouse gases in the Earth's atmosphere are largely transparent to incoming visible radiation, but absorb most of the outgoing long-wave infra-red radiation.

Consider the situation if the atmosphere contained no greenhouse gases and was completely transparent to radiation. The Stefan-Boltzemann law ($B = \varepsilon\ \sigma\ T^4$), relates the temperature of a radiating body to the energy it emits, where B (in Wm^{-2}) is the flux emitted per unit area, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W\ m^{-2}K^{-4}$), T is temperature in ^oK and ε is the emissivity. The surface of the Earth effectively radiates as a black-body: i.e. ε = 1. Averaged over the surface of the Earth, B is 240 Wm^{-2} (i.e. the 342 Wm^{-2} of incoming solar radiation, less the 102 Wm^{-2} directly reflected back into space – see **Figure 1.5**). Solving this equation for B = 240 gives a temperature of 255 ^oK or -18 ^oC. This is 32^oC lower than the average temperature of 14^oC at the Earth's surface. If it were not for the greenhouse gases in our atmosphere, we would live on a frozen world at -18^oC.

A simplified view of the physics of the greenhouse effect is as follows.
From the Stefan-Boltzmann law, the radiation (B_{earth}, almost all in the infra-red) emitted by the surface of the Earth (treated as a black body with ε **=** 1) is given by
$B_{earth} = \sigma T_e^4$
where T_e is the surface temperature in degrees Kelvin. Consider the atmosphere as a single box, with an *equivalent* temperature of T_a and an emissivity (equal, by Kirchoff's Law, to absorptivity) of ε_a. Atmospheric ε_a is less than 1, typically 0.4 – 0.8 for a clear sky, so that the atmosphere will absorb only part of the incident radiation. The atmosphere absorbs $\varepsilon_a\sigma T_e^4$ from the upcoming radiation, allows $(1- \varepsilon_a)\sigma T_e^4$ to be transmitted to space and re-emits $\varepsilon_a\sigma T_a^4$ to space. The total emission to space is then

$$B_{space} = (1- \varepsilon_a)\ \sigma T_e^4 + \varepsilon_a\sigma T_a^4$$
$$= \sigma T_e^4 - \varepsilon_a(\sigma T_e^4 - \sigma T_a^4)$$

The second term in this equation, $\varepsilon_a(\sigma T_e^4 - \sigma T_a^4)$, is popularly known as the 'greenhouse effect'. It becomes greater (i.e. more negative) as the difference between surface temperature and atmospheric temperature increases and also when the atmospheric emissivity ε_a increases. Atmospheric emissivity increases as the concentration of greenhouse gases increases, i.e. the atmosphere behaves more and more like a black body. In essence, what this equation says is that the atmosphere absorbs a portion of the upcoming infra-red radiation from the Earth's surface and emits $\varepsilon_a\sigma T_a^4$, which is less than it absorbs. For the energy balance of the Earth shown in **Figure 1.5**, the upward infra-red radiation from the surface is 396 Wm^{-2}, of which 240 Wm^{-2} reach space, giving a greenhouse effect of 156 Wm^{-2}.

The above treatment of the greenhouse effect is largely taken from Harvey. 2000. *Global Warming: The Hard Science*, Pearson Education. Harvey also gives a more realistic treatment of the greenhouse effect in which the atmosphere is not treated as a single box. This is based on the energy balance at different heights in the atmosphere and does not ignore energy transport in the atmosphere caused by convection or by the evaporation and condensation of water.

The infra-red radiation emitted by the Earth and trapped by greenhouse gases in the atmosphere is re–radiated in all directions. The surface then receives not only radiation coming directly from the Sun, but also the *downward* infra-red radiation coming back from the greenhouse gases in the atmosphere. This is often (and incorrectly) cited as the complete explanation of the 'greenhouse effect'. In reality, the trapping of outgoing radiation, as in the above equation for B_{space}, is far more important. It is perhaps worth noting that real greenhouses keep warm by an entirely different process - by preventing the escape of air heated by the Sun.

1.6 Radiative forcing

This is a key concept in understanding global warming. As already stated, at equilibrium the incoming radiation at the top of the atmosphere is exactly balanced by the radiation emitted, so that the average *net* radiation at the top of the atmosphere is zero. A change in either the incoming radiation or the outgoing radiation will cause the net radiation at the top of the atmosphere to be no longer zero: the imbalance, measured in Wm^{-2}, is called radiative forcing. A positive radiative forcing tends to warm the surface on average, whereas a negative radiative forcing will tend to cool it. The system will slowly adjust (by warming or cooling), so that the net radiation at the top of the atmosphere is again zero. Radiative forcing can arise from natural events, for example by a *change* in the output from the Sun or from human activities, such as a *change* in the natural carbon dioxide concentration caused by industrial activity.

Note. Although radiative forcing, as defined above, should be measured at the *top* of the atmosphere, in practice it is measured at the top of the troposphere – for reasons see Appendix 6.1 in IPCC, 2001: *Climate Change*, I. The operative definition in IPCC, 2001: *Climate Change* I, Annex 1, is as follows. 'Radiative forcing is the change in net, downward minus upward, irradiance (expressed in Wm^{-2}) at the tropopause, due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun'.

Table 1.1 gives the radiative forcing in 2005 for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and two industrial halocarbons, as well as their atmospheric lifetimes and their concentrations in pre-industrial times and in 2005. Although the concentrations of methane and nitrous oxide in the atmosphere (see **Sections 2.10 and 2.13**) are some three orders of magnitude less than that of carbon dioxide, their radiative forcings are only an order of magnitude less than that of carbon dioxide. Radiative forcing does not increase in direct proportion to the concentration of the radiative gas in the atmosphere: thus in **Table 1.1** the radiative forcing for carbon dioxide (ΔF, in Wm^{-2}) in 2005 is calculated from the following logarithmic expression, taking the pre-industrial level to be 278 ppm.

$$\Delta F = 5.35 \ln(\text{concentration in 2005}/\text{concentration in 1750}) = 5.35 \ln(379/278) = 1.66\ Wm^{-2}.$$

The Global Warming Potential (GWP: see **Table 1.1**) is a useful way of assessing the effectiveness of different greenhouse gases in causing global warming. GWP is defined as the radiative forcing for a mass of a particular gas over a specified period, relative to that of the same mass of carbon dioxide over the same period. It varies with the period chosen, as might be expected. Thus a gas with a high radiative forcing and a short atmospheric lifetime will give a GWP that is much larger if calculated over a twenty year span than if calculated over a hundred year period. Conversely, a gas like nitrous oxide, with a relatively long lifetime in the atmosphere, will have a GWP relative to carbon dioxide which changes relatively little whether calculated over 20 or 100 years. The atmospheric lifetime given in **Table 1.1** for carbon dioxide is approximately four years: this is the average time spent by a molecule of carbon dioxide in the atmosphere. It must not be confused with the time taken to reach a new equilibrium if (say) the annual input of carbon dioxide from human activities is doubled - this period is a matter of many centuries, because of slow exchange between the atmosphere and the vast carbon reserves in sea and land - see **Chapter 2.5.**

Table 1.1 **Greenhouse gases before and after the Industrial Revolution**

Gas	Concentration in 1750[a] ppb	Concentration in 2005 ppb	Global Radiative Forcing Wm^{-2}	Atmospheric lifetime[b] years	Global Warming Potential[c] relative to CO_2
Water vapour	2500000		?	~0.02	-
Carbon dioxide	278000	379000	1.66	~ 4	1
Methane	710	1774	0.48	12	25
Nitrous oxide	270	319	0.16	114	298
Tropospheric ozone	25	34	0.35	~0.002	n.a.
CFC-11 ($CFCl_3$)	0	0.251	0.268 [d]	45	4750
CFC-12 (CF_2Cl_2)	0	0.538		100	10900

[a] Sources: David.J.Hofmann@noaa at www.cmdl.noaa.gov/aggi and also cdiac.ornl.gov/pns/current_ghg.html

[b] Atmospheric lifetimes from IPCC I, 2007, Table TS.2 - except for water and CO_2

[c] Global Warming Potential (GWP) calculated over a 100 year period: from IPCC I, 2007, TableTS.2

[d] Aggregated value for *all* halocarbons in the troposphere, including the two in this Table - see Chapter 2.16

1.7 Recent changes in the average temperature of the Earth's surface

Accurate measurements of temperature on the global scale go back little more than a century. **Figure 1.6** shows a rise in annual mean global surface air temperature over the last hundred and twenty five years, interrupted by three decades (1945-1975) when temperatures were relatively constant. This overall rise is the basis for concern about global warming.

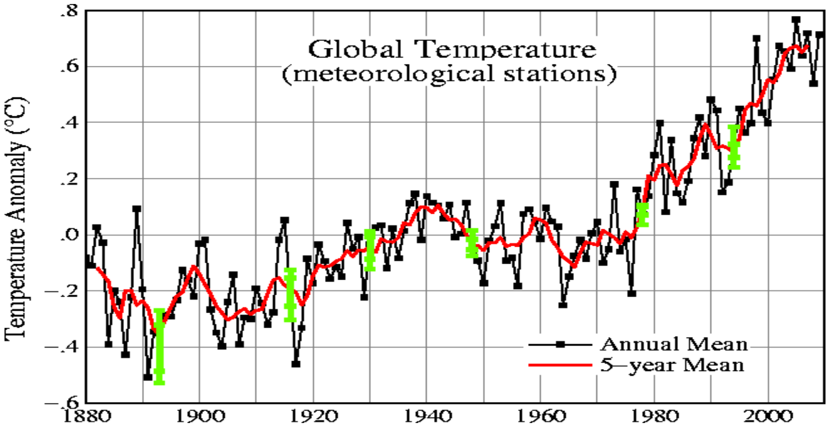

Figure 1.6 Instrumental measurements of changes in global mean land-ocean temperature over the last 125 years, relative to the mean for 1951-1980.

From: data.giss.nasa.gov/gistemp/graphs/. Five year running means in red. Uncertainty bars (95% confidence limits) are shown in green for both the annual and five-year means: these uncertanties allow for incomplete spatial sampling of data.

The period of temperature stability between 1945 and 1975 was most marked in northern mid- and high latitudes. Although carbon dioxide increased steadily during this period, it was also a time when the atmosphere was heavily polluted by sulfate, produced by burning fuels high in sulfur. Sulfate aerosols promote cloud formation, so that more sunlight is reflected: this is thought to be the main reason for the relative stability of surface temperatures between 1945 and 1975 (see Santer et al. 1995. *Climate Dynamics,* **12**, 77-100). Sulfate aerosols will be considered later (**Chapters 2.20 and 6.6**): for now, it is sufficient to observe that the input of sulfur to the atmosphere from human activities has been falling since 1978. Other factors may also have been involved. Particulate lead aerosols are potent initiators of cloud formation. Tetraethyl lead, used as an anti–knock additive to gasoline, could well have led to the formation of lead aerosols in the atmosphere during the mid-century – but the use of tetraethyl lead in gasoline was phased out from the mid seventies. Slow periodic variations in oceanic circulation may also have contributed to this period of temperature stability.

There are considerable year-to-year fluctuations in global mean land-ocean temperature, which is why it is better to rely on running means when looking for long-term trends. Because 1998 was an exceptionally warm year, it has been claimed that the rising trend ended in that year: the five-year running means in **Figure 1.6** argue otherwise.

Before about 1880 we have to rely on indirect ways of establishing temperature. **Figure 1.7** shows reconstructed temperatures in the Northern Hemisphere over the last thirteen hundred years, calculated from a variety of proxy records (ice cores, tree rings etc.), along with the 20th century instrumental record. Although there is much short-term variation,

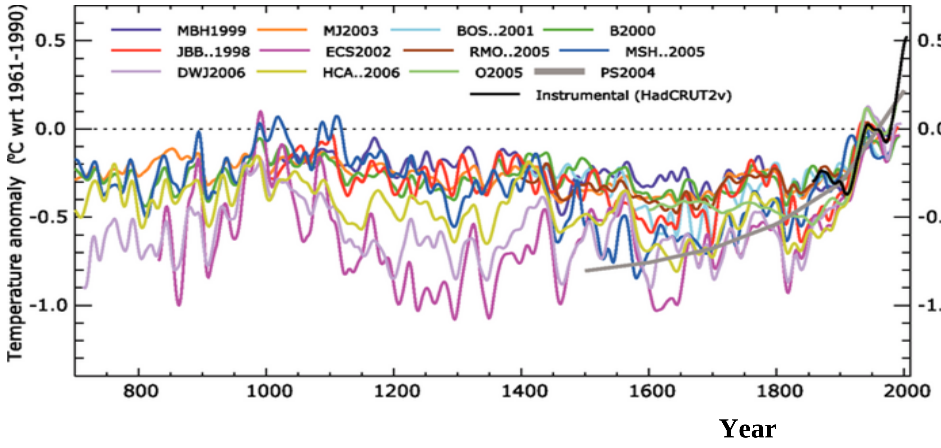

Figure 1.7 Temperature reconstructions back to 700AD for the Northern Hemisphere.

Part of Figure TS.20, IPCC, 2007: *Climate Change.* I. The vertical axis shows temperature anomalies from the 1961-1990 instrumental record mean, in ^{o}C. The black line is from instrumental records; the other coloured lines are various reconstructions based on ice cores, tree rings, bore holes and other indicators of past temperature. The orange line (MJ2003) is from Mann & Jones, 2003. Geophys. Res. Lett. **30**(15), 1820, doi:10.1029/2003GL017814: keys to the other reconstructions are given in Table 6.1, IPCC, 2007: *Climate Change.* I. **Figure 1.7** and similar diagrams are sometimes called 'hockey stick' graphs and have been the cause of much controversy. It has been claimed that the upturn in recent decades is caused by natural variation, not human activities (see, for example, McIntyre & McKitrick, 2005. *Geophysical Research Letters,* **32**, L03710, doi:10.1029/2004GL021750). For a reply to such arguments see Li, Nychka & Ammann. 2007. *Tellus A*, **59**, 591-598.

temperatures in the Northern Hemisphere were relatively warm over the 900-1400 AD period, followed by a cooling, sometimes called the Little Ice Age, which started about 1400 AD and ended in the mid 1800s. However the salient point about **Figure 1.7** is that temperatures over the last decade were the warmest for at least the last millennium.

1.8 Long-term variations in climate caused by changes in the Earth's orbit

The advance and retreat of glaciers over the last couple of million years have been triggered primarily by cyclical changes in the direction of the Earth's axis and its path round the Sun. The three dominant cycles are known as the Milankovitch Cycles - after Milutin Milankovitch, the Serbian astronomer who is generally credited with calculating their magnitude and interactions. They are: variation in the Earth's orbital eccentricity (with a dominant period of some 100000 years), variation in axial tilt (the axis of rotation relative to the plane of rotation round the Sun, with a period of about 41000 years), and precession (the way the axis of rotation moves, rather like a top wobbling as it slows down, with a period of ca. 25800 years). There is another cycle, not considered by Milankovitch, called orbital inclination, in which the Earth moves (with a period of about 100000 years) above and below the plane of mass of the solar system, a plane largely set by the large outer planets, Saturn, Jupiter and Neptune. **Figure 1.8** is a simplified illustration of the three Milankovitch cycles.

The Milankovitch cycles do not appreciably alter the *total* amount of solar radiation reaching the Earth in a year, but operate by altering the contrast between winter and summer. Because most of the Earth's land cover is in the Northern Hemisphere, ice ages are triggered by minima in summer insolation at 60 - 65^{o}N, allowing snow to persist all summer and accumulate, year upon year. This effect is then amplified by the southwards advance of ice, with its greater albedo (i.e. reflectivity: albedo is defined as the fraction of solar radiation reflected by a surface). As albedo increases, more solar radiation is reflected back to space, ice sheets build up, sea level falls and surface temperatures decline.

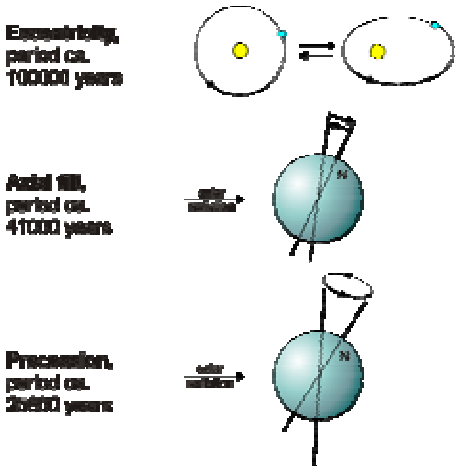

Figure 1.8 The Milankovitch cycles.

The Sun in yellow, the Earth in blue

The best illustration (**Figure 1.9**) of the way the Milankovitch cycles influence climate comes from analyses done on the Vostok ice core, taken from the Antarctic ice sheet, a core that spans four ice ages over the last 420000 years. At the *end* of an ice age, the Milankovitch cycles cause spring to come earlier and autumn later, extending the period of ice melt. Wet ice has a lower albedo than a dry snow cover, further encouraging disintegration of the ice sheets. Albedo decreases even more as the retreating ice exposes bare soil and as sea ice disappears. A rise in temperature follows, followed shortly afterwards by an increase in both carbon dioxide (**Figure 1.9a**) and methane (not shown, but methane tracks carbon dioxide closely). Because carbon dioxide and methane are greenhouse gases, they further intensify warming. The net result is that temperature, carbon dioxide, methane and sea level (at its highest when the ice sheets are at their minimum) track each other closely over all four ice ages.

A salient feature of terrestrial climate change over the last 400000 years is its asymmetry (**Figure 1.9a**). Warming is rapid, because of the strong feedbacks, but cooling takes much longer. It is worth noting that the maximum concentrations of carbon dioxide and methane observed over the past 400000 years, even when the Earth was at its warmest during an interglacial, are far below present concentrations (see **Chapter 2.2 and 2.10**).

It is sometimes argued that since in the past an increase in carbon dioxide did not presage the end of an ice age, neither will the present increase cause an increase in global temperature. Measurements like those in **Figure 1.9** (and more recent measurements on stalagmites from Chinese caves: see Cheng et al. 2009. *Science* **326**, 248-252) show that the rise in temperature at the end of an ice age is closely tracked by a rise in carbon dioxide concentration. In the past the Milankovitch cycles were the trigger. Once this trigger had been pulled, the resulting increases in carbon dioxide and methane amplified the warming process, since both are powerful greenhouse gases. With human-induced warming, carbon dioxide and the other greenhouse gases are themselves the trigger.

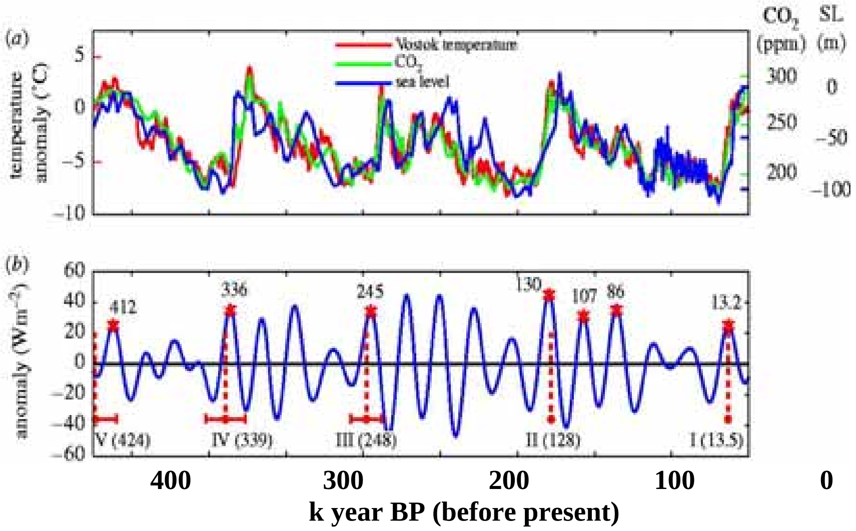

Figure 1.9a Upper diagram shows Antarctic temperature anomaly (calculated from the Vostok ice core: Vimeux et al. 2002)**, atmospheric carbon dioxide concentration** (Petit et al. 1999) **and sea level** (zeroed to modern sea level: Siddall et al. 2003) **over the last four ice ages.**

Figure 1.9b Lower diagram shows the insolation anomaly caused by the Milankovitch cycles in late spring (April, May and June) at 60^o N.

The red stars are calculated insolation maxima: the bracketed numbers are estimated dates for ice age terminations I, II, III, IV and V (Raymo, 1997)
This figure is part of Figure 3 in Hansen et al. 2007. *Phil Trans R. Soc. A,* **365**, 1925-1954, which gives full references to the authors quoted in this legend. Note that the termination of an ice age is triggered by spring insolation in the *Northern* Hemisphere, because that hemisphere contains most of the land surface needed for the buildup of ice sheets. Warming triggered by Milankovitch cycles in the Northern Hemisphere is followed a few millennia later by melting in the Southern Hemisphere (Kawamura et al. 2007. *Nature,* **448**, 912-916).

Further reading for Chapter 1

Andrews, D.G. 2010. *An introduction to atmospheric physics*. Second ED., Cambridge University Press.
New edition of a standard text.

Harvey, L.D.D. 2000. *Global Warming: The Hard Science*. Pearson Education.
What the title says.

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General coverage.

IPCC, 2007: *Climate Change*. I.
The key reference to the subject, as it was in mid-decade.

Maslin, M. 2009. *Global Warming: A Very Short Introduction*. Second Ed., Oxford University Press
An introduction for the non-specialist.

Michaels, P.J. and Balling, R.C. 2009. *Climate of Extremes: Global Warming Science They Don't Want You to Know*. The Cato Institute, Washington DC.
If you **do** want to know what the climate change deniers are now saying.

Hoggan, J., with Littlemore, R. 2009. *Climate Cover-Up: The Crusade to Deny Global Warming*. Greystone Books.
If you **do** want to know more about the climate change deniers and how they are funded.

Chapter 2 – the greenhouse gases

2.1 Water as a greenhouse gas

The natural greenhouse gases carbon dioxide, methane and nitrous oxide have relatively long atmospheric residence times, measured in years and so are well mixed in the troposphere – see **Table 1.1**. Water is different: the residence time of a molecule of water in the troposphere is of the order of a week and the concentration varies hugely with time and from place to place. Estimates based on current climate models (*physicsworld.com/cws/article/print/17402/3*) show that water accounts for about 60 % of the greenhouse effect, with carbon dioxide, tropospheric ozone, methane and nitrous oxide making up the rest. There is just too much water vapour in the troposphere for people to have much of a *direct* effect: the input of water to the troposphere from human activity is less than 1 % of the total content, the major human input being from irrigation of crops. However, the warmer the Earth's surface, the more water is transpired by plant leaves and evaporated from oceans and lakes. Roughly 90 % of the total evaporation comes from water surfaces and 10 % from transpiration.

A warmer troposphere can hold more water and satellite measurements over the last two decades indicate that the concentration of water vapour (i.e. the specific humidity) is increasing. An increase in the concentration of water vapour in the troposphere caused by global warming would produce a positive feedback, increasing the temperature still further. But the more water vapour in the atmosphere, the more clouds, so that more sunlight is reflected back out of the atmosphere (i.e. albedo becomes bigger), giving a negative feedback. Current calculations (IPCC, 2007: *Climate Change*, 1) suggest that the albedo effect is greatest, but there is disagreement between the various climate models on the size of the two opposing effects. There are also indirect effects to be considered – for example, aerosols produced by industry can affect cloud formation and hence change albedo – see **Chapter 2.20**.

The effects of water on absorption of radiation and its re-emission at longer wavelengths are being actively researched at present – the absorption spectrum is extremely complex and still being explored. Likewise, the feedbacks caused by increases in tropospheric water vapour, by changes in cloud cover, etc., are under investigation. To quote from the IPCC, (IPCC, 2007: *Climate Change*, 1, Chapter 3.4.3.2), 'there are substantial uncertainties in decadal trends in all data sets and at present there is no clear consensus on changes in total cloudiness over decadal time scales'.

2.2 Carbon dioxide as a greenhouse gas

The carbon dioxide content of the atmosphere has been increasing since the start of the Industrial Revolution, say in 1750, when it was about 278 ppm. **Figure 2.1** shows the increase over the last 48 years, as measured at the Mauna Loa Observatory in Hawaii, in clean oceanic air, sampled at a height of 3300 metres. Not only has the concentration increased, but the rate of increase has become larger over this period. The average growth rate for the period 2000-2007 was 2.0 ppm per year, compared with a growth rate of about 1.5 ppm per year over the previous twenty years. The annual fluctuations are caused by biological activity in the Northern Hemisphere - plants actively take up carbon dioxide in spring by photosynthesis (see **Chapter 2.4**), releasing oxygen in the process. Later in the year, decay of plant material dominates, with release of carbon dioxide and consumption of oxygen.

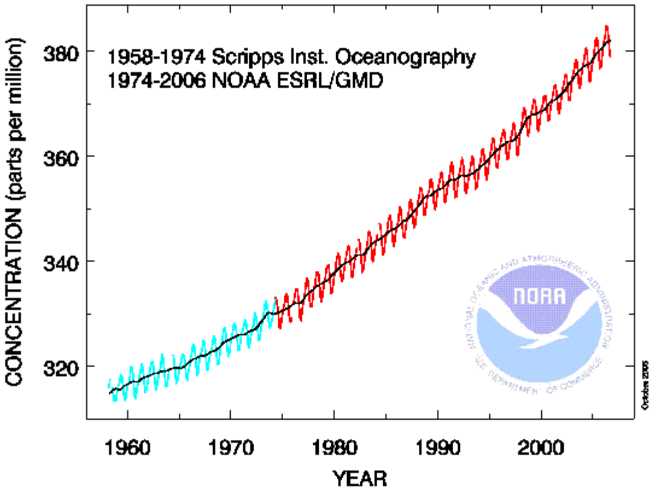

Figure 2.1 Concentration of carbon dioxide in the atmosphere at Mauna Loa Observatory.

From:
www.cmdl.noaa.gov/
publications

2.3 *The natural carbon dioxide cycle*

There are some 40000 Gt of carbon actively cycling between plants, soil, air and ocean, with an annual movement into and out of the atmosphere of about 200 Gt yr^{-1} – see **Figure 2.2**. 'Active' in this context excludes geological carbon that turns over very slowly. There are small movements of carbon into and out of this 'active' pool: every year some dissolved carbon leaves the ocean to join the long-lived sediments on the ocean floor and some carbon dioxide is released by volcanic activity. The long–term average release of carbon dioxide from volcanoes is only 50 Mt CO_2-C yr^{-1} and I shall not consider it further. A molecule of carbon dioxide spends an average time of about four years in the atmosphere

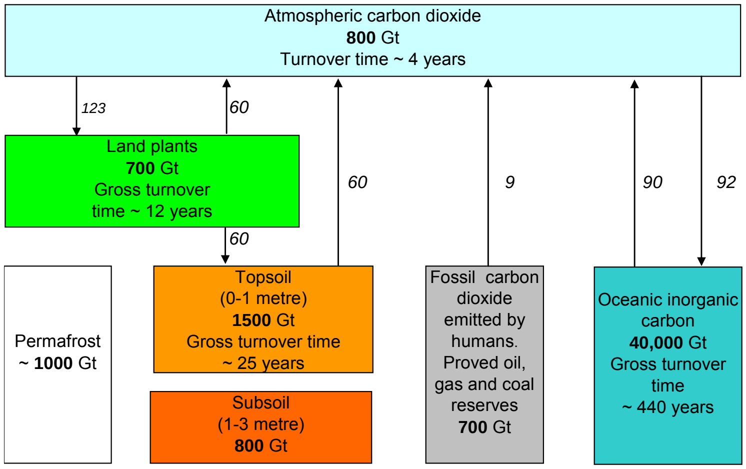

Figure 2.2 An outline of the natural terrestrial and oceanic carbon cycles.

The units in bold are gigatones C: those in italics are gigatones C year^{-1}. This is an updated and simplified version of Figure 7.3 in IPCC, 2007: *Climate Change*. I, with the additional assumption that gross primary production (GPP) is twice net primary production (NPP). Soil excludes peatlands. Soil data from Jobbagy & Jackson. 2000. *Ecological Applications,* **10**, 423-436). At the beginning of 2009 the atmosphere contained 820 Gt CO2-C. Proved oil, gas and coal reserves are for 2008 – see **Table 3.2**.

before being absorbed by the ocean or taken up by land plants (**Table 1.1**). Although the quantities of carbon in the various compartments are reasonably well established, the fluxes between compartments are much less certain. I shall now consider the terrestrial and oceanic parts of the carbon cycle in turn.

2.4 The terrestrial carbon cycle

Plants take up carbon dioxide by photosynthesis:
$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$
In effect, plants use light energy to make a molecule of glucose from six molecules of carbon dioxide and six molecules of water, at the same time releasing six molecules of gaseous oxygen. Part of the energy stored in this glucose is used by the plant to drive its metabolism – to synthesize the cellulose, lignins, proteins, fats, etc. needed for the production of flowers, seeds, roots and so on. This process is described as plant respiration:
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
and proceeds with a release of energy (2808 kJ mol^{-1}). The overall quantity of carbon fixed by photosynthesis is called Gross Primary Production (GPP): that not respired by the plant and remaining as plant carbon as Net Primary Production (NPP). In **Figure 2.2** global GPP is set at 123 Gt C yr^{-1} and global NPP at 60 Gt C yr^{-1}.

In time, the plant sheds leaves, roots, flowers and seeds, in the end dying and falling to the ground. All this plant debris is decomposed by soil organisms. Ultimately all of the carbon in the dead plant is converted back to carbon dioxide by soil respiration:
$\{C\} + O_2 \rightarrow CO_2 + H_2O$
where {C} is plant carbon, commonly about 40 - 45 % of the plant dry weight. The early stages of decomposition are fast, but during these early stages some of the plant carbon is converted to black humic material, which has a half-life of roughly 30 years in temperate soils.

The net effect of photosynthesis and *aerobic* respiration on atmospheric carbon dioxide is zero: a certain quantity of carbon dioxide is consumed and the same quantity is ultimately returned to the atmosphere. Similarly, the evolution of oxygen during photosynthesis is exactly matched by its consumption during aerobic respiration. If not enough oxygen is available, decomposition comes to a halt, with the formation of peat and other anaerobic decomposition products, including methane, an important greenhouse gas – see **Chapter 2.10**. However if the peat is drained, allowing air to enter, decomposition restarts and in the end all the peat is decomposed to carbon dioxide, although the process will take many decades to complete. Organic matter decomposition also stops when the soil is frozen – indeed huge quantities of organic carbon, containing perhaps twice as much carbon as in the atmosphere, are stored frozen in the northern permafrost, part in peat and part in mineral soils. As global warming unwinds, more and more of this stock of organic carbon will be exposed to decomposition. The carbon dioxide thus released will increase atmospheric carbon dioxide concentrations even further – a destabilizing positive feedback. This feedback will be in addition to any positive feedback caused by the release of methane as the permafrost melts – see **Chapter 2.12**. Ominously, current predictions (see **Chapter 4.3**) are that warming will be greatest in these northern lands.

Some people have claimed that an increase in the carbon dioxide concentration of the atmosphere is a good thing and will increase the uptake of carbon dioxide by natural vegetation and also the yields of agricultural crops. Carbon dioxide is of course essential for plant growth – indeed it is used commercially in greenhouses to enhance yields of crops such as tomatoes. However in most natural environments net primary production (NPP) is limited by either temperatures that are too low, by drought, or by insufficient nutrients (particularly nitrogen) - or by some combination of these. Only when these factors (and light) are not limiting, can an increase in atmospheric carbon dioxide result in an increase in net primary production.

2.5 The oceanic carbon cycle

The oceans dominate the carbon cycle, containing roughly fifty times as much carbon as in the atmosphere. Whatever the short-term fluctuations, over the long term (centuries to millennia), the concentration of carbon dioxide in the atmosphere is set by the oceans. Most of the oceanic carbon is inorganic, part as dissolved carbon dioxide (less than 1 %), part as bicarbonate ion (HCO_3^-, about 90 %) and the remainder as carbonate ion (CO_3^{2-}, about 10%). The sum of these three components is termed dissolved inorganic carbon (DIC).

There is a constant exchange of carbon dioxide across the air-sea boundary, presently amounting to about 90 Gt CO_2 C yr^{-1} – see **Figure 2.2**. If the concentration of carbon dioxide in the atmosphere rises at a time when the air/sea system is at equilibrium, there will be a net movement into the sea: if it falls, the net movement will be to the atmosphere. The position of the equilibrium between carbon dioxide in the atmosphere and that dissolved in the surface layer of the sea depends on temperature (cold sea water holds more carbon dioxide than warm), the pH of the surface layer and the salinity. (For details of the chemistry, see the book by Zeebe and Wolf-Gladrow listed at the end of this Chapter).

Although this exchange only takes place at the surface of the sea, the quantity exchanged depends on the continuous replacement of surface water by the action of wind, waves and upwelling of deep water. The layer of mixed water on the ocean surface varies in thickness with weather and latitude: typically it is about 20-30 m in the tropics, increasing to 100-200 m at high latitudes. Below the mixed layer is the thermocline, where there is a rapid fall in temperature, from that of the mixed layer to that of the cold and less turbulent deep ocean.

When carbon dioxide enters sea water it reacts to give carbonic acid:
$CO_2 + H_2O \leftrightarrow H_2CO_3$
Carbonic acid is a weak acid and ionizes to give hydrogen ions (H^+) and bicarbonate ions:
$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$
But in sea water carbonate ions and bicarbonate ions are also in equilibrium:
$CO_3^{2-} + H^+ \leftrightarrow HCO_3^-$
Combining these three equations:
$CO_2 + H_2O + CO_3^{2-} \leftrightarrow 2HCO_3^-$

Thus the main effect of adding carbon dioxide to sea water (which is slightly alkaline, pH ~ 8.1) is the formation of bicarbonate ions, at the cost of the carbonate ions already present. The ability of sea water to take up carbon dioxide therefore *decreases* as carbon dioxide builds up in the atmosphere – in other words, as the ocean becomes less alkaline (and contains fewer carbonate ions) it can neutralize less carbon dioxide. Although exchange between atmospheric and mixed layer carbon dioxide is relatively rapid – with a global turnover time of some seven years - the turnover with the deep ocean is much slower.

Deep oceanic water is eventually returned to the surface by a process called thermohaline circulation (**Figure 2.3**). Thermohaline circulation is driven by two main processes: the cooling of surface water in polar regions and the formation of sea ice, which leaves the remaining unfrozen water more saline. Both factors increase the density of polar surface water, which sinks to the abyss, moving slowly towards the equator, where it rises to the surface again. The overall turnover time of the world's oceans is very approximately two thousand years, but differs widely from ocean to ocean.

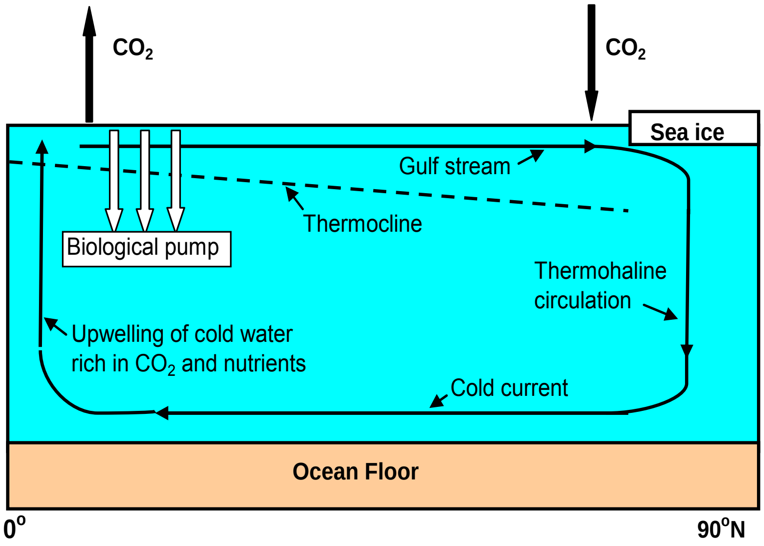

Figure 2.3. The carbon cycle in the Western North Atlantic.

This is a greatly simplified diagram: in reality part of the cold deep south-flowing current continues on to join the Antarctic circumpolar current and the Gulf Stream is reinforced by a warm surface current traveling north up the coast of South America. It ignores mixed layer circulation driven by wind – Ekman transport. The biological pump (see text) moves carbon downwards from the thermocline.

Ocean currents can also be driven by the wind – thus the easterlies that blow across the Pacific along the line of the equator tend to drag the surface water with them, the surface water off Peru being replaced from below by cooler nutrient-rich water. When these easterlies weaken, as they do at irregular intervals of a few years, upwelling ceases and fish desert the warm nutrient-poor surface waters for a few months – an event known to the local fishermen as El Nino, the Christ Child, because it often happens around Christmas. El Nino years have a distinct and characteristic climate pattern that spreads across the tropics and subtropics, far beyond the coasts of Peru, with heavy rain in South America and droughts in Indonesia. El Nino years are frequently interspersed by a countervailing process known as La Nina, in which the easterlies strengthen and water that is even warmer than usual builds up in the Western Pacific, leading to drier conditions in the west Pacific and wetter in the east. There is also evidence for slow rhythmic variation in the surface temperature of the North Atlantic, possibly caused by decadal-scale changes in thermohaline circulation.

The concentration of dissolved carbon dioxide is greater in upwelling water from the deep ocean than in the tropical mixed layer, so that there is a net transfer of carbon dioxide to the atmosphere in the tropics. This difference in concentration is largely the result of two processes that operate in opposite directions. The first, termed the solubility pump, arises because carbon dioxide is more soluble in cold water than hot, so the sinking mixed layer water in polar regions is relatively enriched in carbon dioxide. (*Pumps* are devices that move material *against* a concentration gradient, hence the use of the term to describe certain oceanic processes). The second process, the biological pump, is based on the removal of carbon dioxide from surface water by photosynthetic organisms - the phytoplankton. Since almost all of the incoming light is absorbed in the top 100 m of the sea, this is where the phytoplankton live. Just as with land plants, photosynthesis supplies the energy that drives the reduction of carbon dioxide by water, giving oxygen and glucose, the glucose then being used to drive the phytoplankton life cycle. It is worth noting that most of the photosynthesis in the sea is done by microscopic plants, in contrast to land, where large vascular plants like trees predominate. The total quantity of carbon fixed each year by photosynthesis on land is quite similar to that in the oceans, even though the seas cover much more of the Earth's surface than land (**Table 2.1**). The standing crop of marine autotrophs (i.e. the phytoplankton) is vastly less than that of green plants on land, with the mean turnover time of marine phytoplankton being about 1.5 weeks, compared to some 12 years for land plants.

Table 2.1 Net Primary Production on land and in the sea[a]

	Land	**Oceans**
Mean Primary production, g C m^{-2} yr^{-1}	**400**	**140**
Total primary production, Gt C yr^{-1}	**60**	**52**
Standing crop of autotrophs, Gt C	**700**[b]	**1.5**[c]
Mean turnover time of autotrophs, years	**13**	**0.03**

[a]Based on Brander, (2009). Biological production in the sea - the physical and chemical evidence. ICES, Copenhagen
[b]Green plants: Brander gives 800
[c]Phytoplankton

Phytoplankton are consumed by drifting oceanic animals called the zooplankton, which are in turn consumed by fish and by other creatures higher in the food chain such as whales. The result is a slow rain of organic debris through the thermocline and down into the deep ocean below, where most of it is decomposed by non-photosynthetic organisms to water and carbon dioxide. Only a tiny proportion – of the order of 0.2 Gt C yr^{-1}, reaches the bottom and joins the vast pool of sediments already there. The net result of the biological pump is to remove inorganic carbon from the mixed layer, *against* the upward movement of water from greater depths - see **Figure 2.3**.

Some of the plankton build themelves structures of crystaline calcium carbonate:
$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3\ (\text{solid}) + CO_2 + H_2O$

There are two forms of crystaline calcium carbonate, calcite and aragonite: some organisms form calcite (for example the foraminifera), some aragonite (the corals) and some use both (certain molluscs). As plankton die and fall through the thermocline, the calcium carbonate they contain is carried downwards, a second mechanism for the downward transport of carbon from surface waters. At very great depths (3-4 km) and low temperatures calcium carbonate dissolves, so that calcium carbonate can only accumulate in shallow seas, not on the floor of the abyss.There is therefore a depth (the saturation horizon) above which calcium carbonate is stable, below which it dissolves: this horizon is nearer the surface for aragonite, which is more soluble than calcite.

2.6 Oceanic pH

As the alkalinity of the ocean is neutralized by carbon dioxide released by human activity, its pH will fall. Indeed the global mean *surface* pH has already fallen, from a pre-industrial value of 8.2 to the present 8.1. This process will continue until atmospheric carbon dioxide and oceanic DIC (dissolved inorganic carbon) are again in equilibrium – see the equations for the behavior of inorganic carbon in **Section 2.5**. Currently the oceans absorb about 30 % of the fossil–derived carbon dioxide produced by people (see **Table 2.2**). This

input of carbon dioxide is the immediate cause of ocean acidification, *not* greenhouse warming. However global warming will have a slow additional effect, because, as the oceans warm, the equilibrium between carbon dioxide in the atmosphere and dissolved carbon dioxide in the oceans
$CO_{2\ (atmosphere)} \leftrightarrow CO_{2\ (dissolved)}$
will shift towards the left.

At present the upper layers of the oceans are supersaturated with respect to the carbonate ion CO_3^{2-}, so that organisms with calcareous shells (and also calcareous sediments) are stable. However if the pH falls due to addition of carbon dioxide, calcium carbonate dissolves, using up carbonate ions,
$CaCO_3\ (solid) + CO_3^{2-} + 2CO_2 + 2H_2O \leftrightarrow Ca^{2+} + 4HCO_3^-$
moving the equation to the right. Lower oceanic pHs will therefore work against organisms that construct structures from calcium carbonate, by moving the equilibrium from formation of calcium carbonate towards its dissolution, a problem that is most acute for organisms using aragonite such as the corals. Organisms that need a calcium carbonate structure will therefore be at a disadvantage compared to those that do not, so that complex ecological changes may well follow oceanic acidification. (For an introduction to these and other changes see *Oceanic Acidification Due To Increasing Atmospheric Carbon Dioxide*. The Royal Society. 2005).

2.7 Production of carbon dioxide by human activities

People have been releasing carbon dioxide since prehistoric times, by burning wood for warmth and cooking. Savannas and grasslands were regularly burned as a way of hunting. Farmers cleared land long before the industrial revolution, but the pace has accelerated over the last two centuries, as increasing populations need more food. The burning process can be represented:
$(C_6H_{10}O_5)_n + n\ 6O_2 \rightarrow n\ 6CO_2 + n\ 5\ H_2O$
where $(C_6H_{10}O_5)_n$ is cellulose, the most common constituent of plants. Cellulose is a polymer formed by the condensation of glucose ($C_6H_{12}O_6$), with the loss of water.

Burning of vegetation is 'carbon neutral', i.e. the carbon dioxide taken up when the plants were growing is released when they are burned – apart from a (usually small) portion converted to 'black carbon'. 'Black carbon' is the term given to charcoal, soot and similar materials produced during combustion. The clearance of woodland and scrub by farmers using fire is also 'carbon neutral' – in the sense that the burnt vegetation was formed by photosynthesis some years earlier. However the clearing of forest by fire and its replacement by (say) pasture will release a pulse of carbon dioxide to the atmosphere, since the stock of carbon held in trees and soil is almost always greater than the stock held by the pasture and its underlying soil.

It is only since the industrial revolution that people have started to use fossil fuels on a significant scale. The present consensus is that virtually all of the carbon in fossil fuels was once fixed by photosynthesis, although there is a school which argues that some of the oil and methane was formed by purely chemical reactions. The first photosynthetic organisms to fix carbon dioxide and release oxygen are thought to have been the cyanobacteria (sometimes erroneously called blue-green algae), followed by the oceanic phytoplankton (diatoms and the like) and lastly by the land plants responsible for coal formation. Whatever its origin, the carbon thus fixed (commonly called 'reduced carbon') must then have been protected from oxygen so that it could not be oxidized back to carbon dioxide by microbial decay. Photosynthesis is the source of all the oxygen in the atmosphere, as well as being the source of the oxygen that was used in the remote geological past to convert primeval Fe^{2+} to Fe^{3+}

(forming the haematite iron ores) and S^{2-} to $SO_4{}^{2-}$ (giving sea water sulfate and gypsum beds).

2.8 Where has all the carbon dioxide produced by human activities gone?

From the beginning of the industrial revolution up to the present, people have released some 320 Gt of carbon (as carbon dioxide) from the combustion of fossil fuels and cement manufacture (**Table 2.2**). In 2007 the annual production of carbon dioxide from the combustion of fossil fuels and manufacture of cement was 8.53 Gt CO_2-C, of which about 96 % came from fossil fuel. Cement production involves the heating of clay with limestone or chalk and during the process carbon dioxide is released by the reaction

$CaCO_3 \leftrightarrow CaO + CO_2$

with roughly one tonne of carbon dioxide evolved for every tonne of cement manufactured.

Over the last two centuries, people have also released large quantities of carbon dioxide by logging and by clearing land for agriculture. The carbon dioxide content of the atmosphere has increased by 207 Gt C since 1850 and a further 142 Gt C has been taken up by the ocean (**Table 2.2**). If the numbers in this Table are to balance over the period 1850-2007, the carbon released by land clearance must have *exceeded* that taken up by *new* land and soil sinks by 29 Gt C. By contrast, over the period 2000-2007, the annual release of carbon from land clearance was *less* than that taken up by new land and soil sinks by 1.1 Gt C yr^{-1}. These ‘new’ terrestrial sinks are thought to arise from increased plant growth due to nitrogen fertilization, whether accidental or deliberate, carbon dioxide fertilization (where plant growth is CO_2 limited), longer growing seasons, particularly in high northern latitudes, and reversion of marginal farmland to scrub and forest. According to Carbon Trends (for reference see first footnote to **Table 2.2**), the terrestrial sinks appear to be growing, whereas the efficiency of the oceanic sink in removing carbon dioxide from the atmosphere is declining. This increase in the terrestrial sink would have been even larger, if increased temperatures had not accelerated the decomposition of soil organic matter (Piao et al. 2009, *Global Biogeochem.*

Table 2.2 Fate of carbon dioxide produced by human activity 1850-2007

	Total 1850-2007 Gt C	**Average over 2000-2007 Gt C yr^{-1}**
Released by combustion of fossil fuel and manufacture of cement	**320**[a]	**7.5**
Released by land clearance	**160**	**1.5**
Total released	**480**	**9.0**
Accumulated in atmosphere	**207**	**4.2**
Taken up by sea	**142**[b]	**2.2**
Taken up by land	**131**[c]	**2.6**[c]
Total accounted for	**480**	**9.0**

From: Carbon budget and trends 2007, [www.globalcarbonproject.org, 26 September 2008], except for a and b.

[a] From CDIAC at http//cdiac.ornl.gov

[b] From Sabine et al. Science. 2004. 305, 367-371, extrapolated to 2007.

[c] 'Taken up by land' is a balancing term and subject to large errors.

Cycles, 23, doi:10.1029/2008GB003339). But in the long run, it is probable that the terrestrial sink will reach saturation and start to decline, just as the oceanic sink has already done.

2.9 Methane as a greenhouse gas

Methane is a powerful greenhouse gas: per unit mass, it is 25 times as potent as carbon dioxide (**Table 1.1)**. It has always been a minor constituent of the atmosphere, varying from about 400 ppbv (parts per billion by volume) in the depths of an ice age to 700-800 at the height of an interglacial warm period. Prior to the industrial revolution it was about 710 ppbv, more than doubling to 1780 ppbv in 2008. The atmosphere now contains about 3.5 Gt C in methane.

2.10 Sources of atmospheric methane

By far the greater part of the methane in the atmosphere today comes from the activities of the methanogens - a group of primitive microorganisms belonging to the Archaea. These organisms produce methane under anaerobic conditions, i.e. in the complete absence of oxygen, so they only operate when other microorganisms have removed all the oxygen. Under anaerobic conditions, plant materials such as cellulose are fermented to organic acids. The methanogenic Archaea then convert these acids to methane and carbon dioxide – thus acetic acid is decomposed:

$CH_3COOH \rightarrow CO_2 + CH_4$

The main source of methane is the anaerobic decomposition of organic matter in freshwater swamps and wetlands – its old name was ‘marsh gas’, because of the bubbles of methane that rise from stagnant swamps. Termites are another source: they digest cellulose anaerobically in their guts, releasing methane as a by-product. Methane also comes from ruminants - cows, sheep, horses, etc: as with termites, the methane is a by-product of the metabolism of cellulose by anaerobic microorganisms living in the gut. Plant leaves have been claimed to release methane, a claim that has now been challenged (see Evans. 2007. *New Phytologist*, **175**, 1-4, for a commentary on the controversy).

Industry and agriculture have released much methane over the last 200 years. Paddy rice cultivation produces methane - rice fields are in effect controlled swamps. Where a rice paddy replaces a pre-existing swamp there may not be much change in methane evolution, but methane production will increase when land is flooded for rice production. Numbers of cows and sheep have increased as the human population increases. Coal mining releases trapped methane, as does natural gas production, often through leaky pipelines – natural gas is largely methane. Landfills are another source of methane, produced by the methanogens that live in rotting organic rubbish. Incomplete combustion – for example a smoldering peat fire - also releases methane.

The annual increase in the concentration of methane almost slowed to a stop between 2000 and 2005 (**Figure 2.4**). The most likely explanation is that fewer wetlands were now being drained (see Bousquet et al. 2006. *Nature*. **443**, 439-443) but this may not be the only factor involved – leaky natural gas pipelines have been repaired. Whether or not atmospheric methane resumes its upward climb remains to be seen, although there are indications over the last couple of years that it has. The present global production of methane is thought to be about 0.44 Gt C yr^{-1}, with an annual sink of 0.44 Gt C yr^{-1} (IPCC, 2007: *Climate Change*, I, Table 7.6, where the fluxes are given as Gt CH_4) – but both numbers are only approximate. The turnover time in the atmosphere is about a decade – see **Table 1.1.**

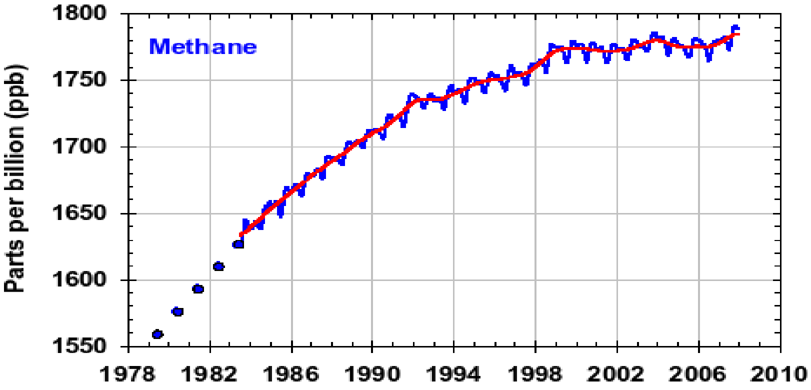

Figure 2.4 Concentration of methane in the atmosphere

From: **THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)** http://www.cmdl.noaa.gov/aggi/**.**
Measurements in blue, averages in red.

2.11 Sinks for atmospheric methane

There are two main sinks for atmospheric methane. Some is consumed by aerobic organisms living in the soil – indeed much of the methane produced in the anaerobic layer of a rice paddy never reaches the atmosphere because it is consumed by other microorganisms living in the overlying (aerobic) layer of soil. Sizeable quantities of methane are taken up by soil organisms – recent estimates of global uptake by soil put this at 15-25 Mt CH_4-C yr^{-1}.

However the most important sink for methane in the atmosphere is through chemical reaction with hydroxyl radicals ($OH^{\cdot}$, although commonly written as OH). This radical, one with a central role in atmospheric chemistry, is formed by photolysis of ozone by sunlight:
$O_3 + H_2O \rightarrow O_2 + 2\ OH$
Another important source of hydroxyl is photolysis of water, particularly in the stratosphere.
The hydroxyl radical reacts with methane to give a CH_3 radical:
$OH + CH_4 \rightarrow H_2O + CH_3$
The methyl radical then reacts with oxygen, ultimately giving CO_2 and water. Methane thus takes an active part in atmospheric chemistry, in contrast to carbon dioxide.

2.12 Geological reserves of methane

Most of the world's known reserves of methane (see **Table 3.2**) are stored deep underground under impermeable rock domes or trapped in coal seams. However, large quantities of methane gas are also held as solid methane hydrates, the gas being trapped between water molecules in an ice. Methane hydrates are stable over certain well-defined conditions of temperature and pressure. They can exist under normal atmospheric pressure when the temperature is permanently below 0 °C, i.e. at high latitudes in the permafrost zone.

They are also found in oceanic sediments where the bottom temperature is around 2 °C and the pressure sufficient to prevent break-up to water and methane gas. Most of the oceanic methane hydrate so far located is on the continental shelves, at depths of 300-500 m. Earlier estimates of the quantity of methane held as hydrate have been downgraded, but there is still great uncertainty about the size of this reservoir: one estimate puts the marine inventory at 500-2500 Gt C (Milkov. 2004. Earth Science Reviews. **66**, 183-197).

There is also an estimated 400 Gt C in the methane of the Arctic permafrost reservoir. The rise in atmospheric methane that follows the end of an ice age may well have come from the decomposition of methane hydrates as the permafrost thaws. Global warming is at its strongest in the circumpolar regions and the first large release of methane could well come from permafrost thawing, long before the oceans have warmed sufficiently to allow the marine hydrates to break down and release their methane.

2.13 *Nitrous oxide as a greenhouse gas*

Gram per gram, nitrous oxide (N_2O) is roughly three hundred times more potent as a greenhouse gas than carbon dioxide (**Table 1.1**). This means that it is a significant greenhouse gas, even though the concentration of carbon dioxide in the atmosphere is now more than a thousand times greater than the concentration of nitrous oxide. Like carbon dioxide and methane, nitrous oxide has increased with industrialization, from about 270 ppb in 1800 to 322 in 2008 (**Figure 2.5).**

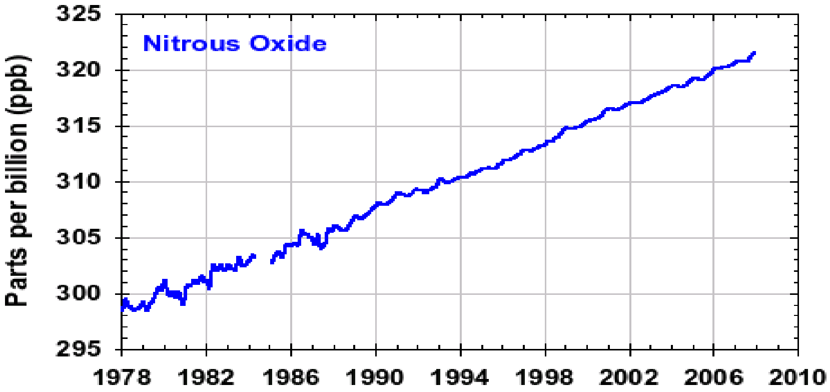

Figure 2.5 Concentration of nitrous oxide in the atmosphere.

From: **THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)** http://www.cmdl.noaa.gov/aggi/

2.14 *Sources of nitrous oxide*

Natural inputs of nitrous oxide to the atmosphere (expressed as N) are in the region of 11 Mt N yr^{-1}, with human activity accounting for an additional 7 Mt N yr^{-1}, although both figures are very uncertain (IPCC, 2007: *Climate Change*. I, Table 7.7). Most of the nitrous oxide in the atmosphere comes from microbial activity, although there are small direct contributions from fires, internal combustion engines and the chemical industry. In this it is similar to carbon dioxide and methane, biological activity being the dominant source for all three gases.

Nitrous oxide is formed as a by-product in nitrification, a two-stage microbial process found in all soils (except the most acid), that converts ammonium (NH_4^+) first to nitrite (NO_2^-) and then to nitrate (NO_3^-). Usually only a percent or two of the nitrogen undergoing nitrification is lost as nitrous oxide.

By far the most important microbial process producing nitrous oxide is denitrification - the decomposition of nitrate under anaerobic conditions. Denitrification is the name given to the sequence of reactions:
nitrate (NO_3^-) → nitrite (NO_2^-) → nitric oxide (NO) → nitrous oxide (N_2O) → nitrogen gas (N_2).
Denitrification takes place in soils, swamps, lakes, rivers and at the bottom of the ocean – wherever a microbial population that is actively decomposing organic matter runs out of free oxygen. The population then uses any nitrate that may be present as a source of oxygen (i.e. as an electron acceptor). If the concentration of nitrate is high and the environment only moderately anaerobic, nitrous oxide will be evolved. In strongly anaerobic environments, nitrogen gas is the main product.

Most of the increase in atmospheric nitrous oxide over recent decades has come from agriculture. The clearing of tropical forest for pasture increases the production of nitrous oxide, as does the introduction of leguminous crops such as soybeans, through their ability to fix atmospheric nitrogen, some of which inevitably ends up as nitrate. The use of nitrogenous fertilizer has increased greatly since the early years of the last century, when Fritz Haber found out how to manufacture ammonia from nitrogen and hydrogen. Between 1978 and 2005 (inclusive) 2670 Mt of fertilizer N were made. Over the same period, the atmospheric burden of nitrous oxide (as N) increased by 96 Mt N. If we assume that *all* of the increase in nitrous oxide came from fertilizer, and correct for decomposition of nitrous oxide in the atmosphere, then *at most* 4 % of the fertilizer N was converted to nitrous oxide. The true figure will be less than this, because other human activities also released nitrous oxide over this period – industry, biomass burning, cultivation of legumes, etc.

2.15 Sinks for atmospheric nitrous oxide

Nitrous oxide is very stable in the troposphere, the only known source of loss being a small quantity reduced to nitrogen gas by soil microorganisms. It is mostly decomposed photochemically in the stratosphere:
N_2O + ultra violet light → $N_2 + O(^1D)$
where $O(^1D)$ is atomic oxygen in an excited state. This reaction accounts for about 90% of the nitrous oxide decomposed, with the remaining 10% decomposed by the reaction
$N_2O + O(^1D) \rightarrow 2\ NO$

The atomic oxygen produced by the first reaction increases the decomposition of nitrous oxide by the second reaction, so that the lifetime of nitrous oxide in the atmosphere falls as its concentration increases. The lifetime of nitrous oxide given in **Table 1.1** (114 years) is corrected for this effect: uncorrected it would have been about 120 years.

2.16 Halocarbons as greenhouse gases and as ozone depletors

Halocarbon is the term given to carbon compounds containing halogens – fluorine, chlorine, bromine and iodine. For convenience, another volatile gas, sulfur hexaflouoride (SF_6), although not a halocarbon, will be considered along with them. Some of the volatile

Table 2.3 **Some industrial halocarbons (as well as sulfur hexafluoride) and their potential action as greenhouse gases and as ozone depletors**

Class	Trade name	Chemical formula	Status under Montreal Protocol	Ozone depleting potential[a], relative to CFC-11	Global Warming Potential[b], relative to CO_2	Atmospheric lifetime[b] years
Chlorofluorocarbons (CFCs)	CFC-11	$CFCl_3$	Phased out	1	4750	45
	CFC-12	CF_2Cl_2	Phased out	1	10900	100
Hydrochlorofluorocarbons (HCFCs)	HCFC-22	CHF_2Cl	To be phased out	0.05	1810	12
	HCFC-141b	CH_3CFCl_2	To be phased out	0.1	725	9
	HCFC-142b	CH_3CF_2Cl	To be phased out	0.06	2310	18
Hydrofluorocarbons (HFCs)	HFC-125	CHF_2CF_3	In use	0	3500	29
	HFC-134a	CH_2FCF_3	In use	0	1430	14
	HFC-143a	CH_3CF_3	In use	0	4470	52
Perfluorocarbons (PFCs)	PFC-14	CF_4	In use	0	50000	7390
Sulfur hexafluoride		SF_6	In use	0	22800	3200

[a] From http://www.epa.gov/ozone/ods.html and related epa websites

[b] From IPCC, 2007: *Climate Change*. I. Table TS.2

halocarbons are manufactured in large quantities, mainly for use in refrigeration, in air conditioning, in the production of insulating foams and in the manufacture of electronic goods. As well as being powerful greenhouse gases in themselves, certain halocarbons can deplete ozone in the stratosphere. **Table 2.3** lists some of the more important halocarbons and their effects on the environment: for complete lists see the US Environmental Protection Agency (epa) websites listed in the Table footnotes.

2.17 Ozone depletion by halocarbons

Ozone (O_3) is present in both troposphere and stratosphere. Stratospheric ozone is a strong absorber of ultra-violet light and is the major filter for UVB (wavelength 290-320 nm), the biologically-harmful part of solar radiation. A decrease in stratospheric ozone will therefore allow more UVB to reach the Earth's surface. Ozone depletion is a term covering two related observations: a slow decline of about 0.3% a year in the amount of ozone held by the whole stratosphere over the last twenty years and a much larger, but seasonal, decline in ozone over the poles, particularly Antarctica, again as measured over the last twenty years.

Ozone is continually being formed and destroyed in the stratosphere by the Chapman reactions:
O_2 + ultra-violet light $\rightarrow$ O + O
$O_2 + O \rightarrow O_3$
O_3 + ultra-violet light $\rightarrow$ O_2 + O
$O_3 + O \rightarrow 2O_2$
However, the last reaction is so slow that other reactions must also be involved, otherwise levels of stratospheric ozone would be much greater than observed. These additional reactions almost certainly involve the atomic halogens. Atomic chlorine and, even more effective,

atomic bromine, are produced by photochemical decomposition of certain halocarbons in the stratosphere and these rapidly react with ozone:
$Cl + O_3 \rightarrow ClO + O_2$
$ClO + O \rightarrow Cl + O_2$
Overall the reaction is
$O_3 + O \rightarrow 2O_2$
just as in the last of the Chapman equations, but with each chlorine atom acting as a catalyst, able to decompose many ozone molecules. However at any given time, only a tiny portion of the chlorine in the stratosphere exists in the atomic form: most is in stable ‘reservoir’ compounds, predominantly hydrochloric acid (HCl) and chlorine nitrate ($ClNO_3$).

In the Antarctic winter, icy clouds form in the stratosphere and these ‘reservoir’ compounds (formed months or years earlier, not necessarily over the poles) condense on the ice surfaces. When the Sun returns in spring, the ice clouds melt, releasing the trapped compounds. Atomic chlorine is released photochemically from the ‘reservoir’ compounds and the chlorine atoms then proceed to mop up ozone held within the polar vortex - a system of strong westerly circumpolar winds that builds up in the Antarctic spring, effectively isolating this part of the atmosphere. As spring advances, the vortex breaks up and the ozone hole disappears. There is also an Arctic ozone hole, but it is smaller, since winter temperatures are higher and the polar vortex less marked than at the South Pole.

The Montreal Protocol of 1987 was the first international response to a growing realization that certain industrial halocarbons were damaging the ozone layer. Under the Protocol, the chlorofluorocarbons (CFCs, notably first two listed in **Table 2.3**) were to be phased out and replaced by the less damaging hydrochlorofluorocarbons (HCFCs). Halocarbons are now rated in terms of their ozone depleting capacity with respect to CFC-11 ($CFCl_3$), which is set at one. The HCFCs have values that are 0.1 or less; the perfluorocarbons (PCFs) have values that are essentially zero (**Table 2.3)**.

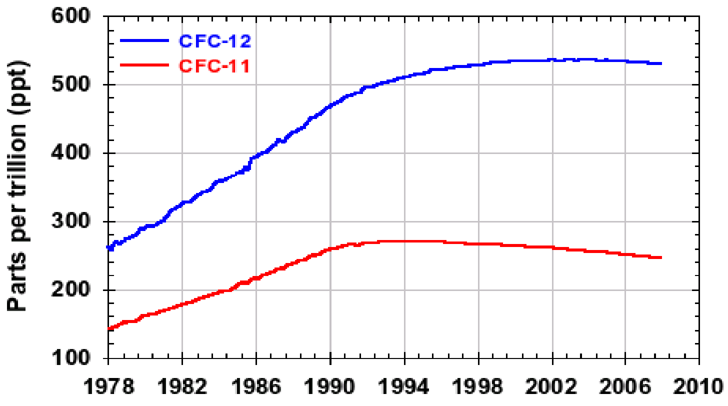

Figure 2.6 Atmospheric concentrations of halocarbons CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2)

From: **THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)** http://www.cmdl.noaa.gov/aggi/

Atmospheric concentrations of the now-banned chlorofluorocarbons CFC-11 and CFC-12 peaked about the turn of the millennium and have now started to decrease (**Figure 2.6**). Although it is too soon to be sure, there are suggestions that the ozone hole has now stabilized and recovery may be about to start – the ozone holes over the South Pole in 2007, 2008 and 2009 were smaller than that in 2006, the largest and deepest ever recorded.

Industry is not the only source of volatile halocarbons: chloroform ($CHCl_3$) and methyl chloride (CH_3Cl) are evolved from both land and sea. Some 700 kt of chloroform are released per year, 90% from natural sources. Other chlorinated, brominated and iodated halocarbons are evolved naturally in lesser quantities. However these naturally-produced compounds are rapidly destroyed in the troposphere (for example the residence time of chloroform is four months), and so contribute little to stratospheric ozone destruction.

2.18 Halocarbons as greenhouse gases

Although international action has been successful in mitigating the effects of industrially-produced halocarbons on the ozone layer, halocarbons are also powerful greenhouse gases and here the situation is far less optimistic. All the halocarbons absorb infra-red light at the frequencies radiated by the Earth and so behave as greenhouse gases in the troposphere. Calculated over a hundred year period, their Global Warming Potentials (GWPs) are many times that of carbon dioxide (**Table 2.3**). Their long lifetimes in the atmosphere contribute to these large GWPs, particularly in the case of the perfluorocarbons and sulfur hexafluoride. Thus carbon tetrafluoride has an atmospheric lifetime of nearly six thousand years and is 50000 times more effective as a greenhouse gas, kilogram per kilogram, than carbon dioxide (**Table 2.3**).

With these huge GWPs, it is not surprising that radiative forcing from the combined halocarbons is now nearly a fifth of that from carbon dioxide (**Table 1.1**), even though the halocarbons are present in only a few millionths of the concentration of carbon dioxide. Halocarbons will remain in the atmosphere long after humans have learnt how to control the release of carbon dioxide - or have run out of fossil fuel.

2.19 Ozone as a greenhouse gas

As we have seen in **Chapter 2.17**, ozone is a highly reactive gas, continuously being formed and broken up in the atmosphere. It is poorly mixed, varying both vertically (**Figure 2.7**), horizontally and from hour-to-hour, unlike other more stable (and therefore well mixed) greenhouse gases such as carbon dioxide, methane, nitrous oxide or the halocarbons. Since human activities are causing ozone concentrations in the stratosphere to decline, radiative forcing in this layer of the atmosphere is negative and the stratosphere is becoming cooler as ozone concentrations fall. Because ozone concentrations are so variable, the size of this forcing is difficult to calculate exactly: estimates for global forcing in the stratosphere range from -0.15 to 0.05 Wm^{-2}, the preferred estimate (IPCC, 2007: *Climate Change.* I, Figure TS 5) being -0.05Wm^{-2}.

About 90% of the ozone in the atmosphere is in the stratosphere, with the other 10% in the troposphere. A relatively small part of the ozone in the troposphere comes from the stratosphere by downward transport, and thus is ultimately generated by the photolysis of oxygen by UV light – see **Chapter 2.17**. The remainder is formed by the action of sunlight on oxides of nitrogen (NO_x), carbon monoxide (CO) and volatile organic compounds (VOCs), such as those in gasoline fumes or emitted from vegetation. (NO_x is the symbol used for an unspecified mixture of nitric oxide (NO) and nitrogen dioxide (NO_2)). These compounds are all found in urban smog, so this ozone is mostly generated in summer, in the middle of the day, near the ground and downwind of large cities.

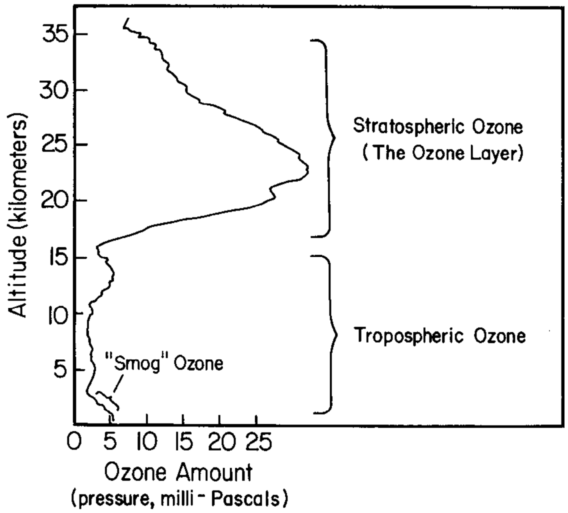

Figure 2.7 How ozone varies with height in the atmosphere

From: www.ozonelayer.noaa.gov/science/basics.htm

Ozone units are mPa, where there are 1.013 x 10^8 mPa in one atmosphere

The main source of atomic oxygen *in the troposphere* is the photochemical dissociation of nitrogen dioxide:
NO_2 + ultra-violet light $\rightarrow$ NO + O
Ozone is then formed by the reaction of this atomic oxygen with O_2
$O + O_2 \rightarrow O_3$
just as in the stratosphere (**Chapter 2.17**).
Combining these two equations gives the reversible reaction
$NO_2 + O_2 \leftrightarrow NO + O_3$

A high concentration of NO_2 will drive the equation to the right, forming ozone, whereas a high concentration of NO will force the reaction to the left, thus destroying ozone. Ozone is thus continually being formed and decomposed – but the concentration remains low unless there is another way of generating NO_2 from NO, one that does not destroy ozone. This is provided by the oxidation of VOCs: without them, NO_2 on its own is incapable of producing the ozone concentration found in urban smogs. The oxidation of VOCs (including in this context carbon monoxide and methane) in the atmosphere is an extremely complex process, catalysed by NO_x. The ultimate products are water, carbon dioxide and, under the right conditions, ozone - for details see the book by Finlayson-Pitts and Pitts listed at the end of this Chapter.

Ozone has a lifetime of only a week or two in air near the ground. Not only is tropospheric ozone a powerful greenhouse gas in itself, in high concentrations it is a lung irritant and can also damage plant leaves, reducing crop yield. The EC 'alert threshold' for human health is 120 ppb, averaged over one hour, compared to levels of 10 - 15 ppb in 'clean' tropospheric air. The US EPA defines an average concentration of 80 ppb over 8 hours as an 'exceedance'. In the past, ozone concentrations in Los Angeles sometimes reached 500 ppb, before emission controls on ozone precursors were introduced.

Although most tropospheric ozone is recycled in the atmosphere as described above, some is destroyed by deposition on vegetation and soil, the quantity thus destroyed being comparable with that descending from the stratosphere. It is worth contrasting the behaviour of NO_x and N_2O. The influence of NO_x is confined to the troposphere, where it has a lifetime of only about a day, so that virtually none has time to reach the stratosphere. The much less reactive N_2O is present in the same concentration in troposphere and stratosphere, where, as we have seen in **Chapter 2.15**, it is slowly decomposed by ultra-violet light.

Ozone absorbs infra-red light over the frequencies emitted by the Earth and so is a greenhouse gas. Since human activities have increased ozone concentrations in the troposphere, the radiative forcing is positive, in contrast to the stratosphere, where concentrations have decreased, generating a negative forcing. The global average radiative forcing caused by increases in tropospheric ozone since pre-industrial times is given (IPCC, 2007: *Climate Change.* I, Figure TS 5) as 0.35 Wm^{-2}, with a spread of 0.25 to 0.65. The spread is extremely wide because pre-industrial concentrations (and, for that matter, present concentrations) are so ill-defined. None the less, the present view is that tropospheric ozone is the third most important cause of radiative forcing, immediately after carbon dioxide and methane.

2.20 Atmospheric aerosols

Aerosols are liquid or solid particles suspended in the atmosphere. They have direct effects, in that they can both absorb and reflect back part of the visible and infra-red radiation coming from the Sun. As well as these direct effects, aerosols can also alter the amount, lifetime and radiative properties of clouds (for more about this see **Chapter 6.6**). The most significant, both quantitatively and for their influence on climate, are, in order, mineral dust (from dust storms and volcanoes), sea salts (from evaporation of ocean spray), sulfates (from both industrial and natural sources) and black carbon (from incomplete combustion, human generated or otherwise).

Aerosol concentrations vary hugely in space and time – think of the dust cloud hurled into the stratosphere by the explosion of Mount Pinatubo in 1991, or of the enormous emissions of sulfur from industry that peaked in the 1970s, before controls were enforced. Volcanic dust reflects incoming radiation back to space, increasing albedo and thus leading to tropospheric cooling. Aerosols are rapidly rained out of the troposphere, with lifetimes of a week or so, but can persist for much longer in the stratosphere. The explosion of Mount Pinatubo caused a negative forcing of -4 Wm^{-2} at the beginning of 1992, falling exponentially to about -0.1 after four years. Global surface temperature fell by about 0.5 ^{o}C in the year following the explosion.

Aerosol sulfate comes in part from salt spray, but mainly from oxidation of sulfur dioxide. Some of this sulfur dioxide is emitted from the combustion of ‘dirty’ fuels, particularly high-sulfur coal, some comes from volcanic activity and some comes indirectly, from the oxidation of dimethylsulfide (CH_3SCH_3), a volatile sulfur compound released by marine plankton. Human activities dominate: averaged over the decade 1991-2000, the annual release by industry was 63 Mt S, by volcanoes 10 Mt S and from the oceans 20 Mt S.

Sulfur dioxide is oxidized to sulfuric acid by a complex series of catalytic reactions, the overall reaction being:

$SO_2 + O + H_2O \rightarrow H_2SO_4$

Sulfate in aerosols is present as sulfuric acid, neutralized to a variable extent by ammonia, giving ammonium sulfate. These aerosols serve as condensation nuclei in the formation of clouds, but they also influence both droplet size and number, and hence the amount of water that falls from a cloud as rain.

Sulfate aerosols are considered to be a major cause of the cooling between 1945 and 1975 (**Figure 1.6**). Anthropogenic emissions of sulfur, mostly from industry, peaked in 1978 at 75 Mt S yr^{-1} and by 2000 had declined by 20%. However rapid industrialization in the decade 2000-2010, particularly by China, has altered this trend. Emissions of SO_2 by China rose from 11 Mt S yr^{-1} in 2000 to 17 Mt S yr^{-1} in 2006, mainly from coal-fired electricity generating plants. Over this period, these emissions led to marked light dimming (caused by an increase in cloudiness and ‘brown’ clouds), as well as to an increase in acid rain over East

Asia. However there are indications (Lu et al. 2010. *Atmos. Chem. Phys. Discuss.*, **10**, 8657-8715) from satellite measurements that this trend has started to reverse, following the recent installation of desulfurization devices in Chinese power stations.

Black carbon (soot) is released to the atmosphere during incomplete combustion, where it absorbs incoming radiation and thus causing a positive radiative forcing. Because of the difference in sign, radiative forcing by particles of black carbon tends to cancel forcing by sulfate aerosols. However because an individual aerosol particle can contain both soot *and* sulfate, the two effects are not necessarily additive. In addition to its role as an aerosol, black carbon falling on snow will decrease albedo.

The current best estimate (Myhre, 2009. *Science*, **325**, 187-190) of the direct global radiative forcing by aerosols is -0.3 ± 0.2 Wm^{-2}. The indirect effect, arising through the effects of aerosols on cloud formation, is set at -0.7, with a spread of -1.8 to -0.3 (IPCC, 2007: *Climate Change.* I, Figure TS 5). These huge spreads are a reflection of the uncertainties in present knowledge, particularly the indirect influence of aerosols on the formation and persistence of clouds.

2.21 Radiative forcing - a summary

Current estimates of radiative forcing are summarized in **Figure 2.8,** which is arranged with the most firmly established values on the left and the most uncertain towards the right. Forcings caused by changes in the water content of the atmosphere and by volcanic eruptions are excluded, as are changes in solar irradiance, estimated at +0.12 Wm^{-2} (IPCC, 2007: *Climate Change.* I, Figure TS 5).

A most important point must be made in considering **Figure 2.8:** *apart from carbon dioxide*, all the gaseous contributors to radiative forcing are removed from the atmosphere by photolysis, by chemical reaction or by rainout. To a first approximation, a 10 % increase in the annual input of a gas like methane will eventually lead to a 10 % increase in its concentration in the atmosphere. In contrast, carbon dioxide is stable in the atmosphere, so that a 10 % increase in the annual input of carbon dioxide will build up in the atmosphere,

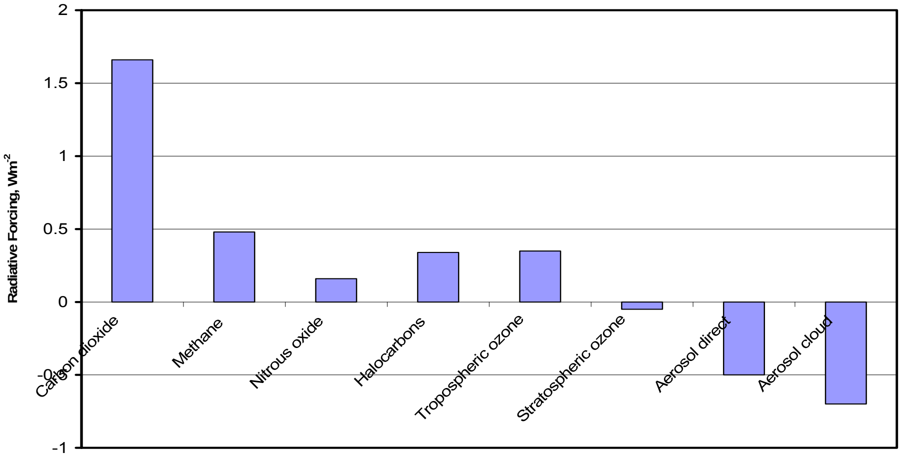

Figure 2.8 Radiative forcing in 2005 by anthropogenic changes in atmospheric gases and aerosols

Based on Figure SPM.2 in IPCC, 2007: *Climate Change.* I. Note that Myhre (2009. *Science*, **325**, 187-190) puts the direct radiative forcing by aerosols as rather less: -0.3 ± 0.2 Wm^{-2}.

year after year, except for that portion taken up by the three great carbon sinks, the oceans, land plants and soils. In the long term, relatively little carbon will accumulate in soils and vegetation, because here plant nutrients and rainfall are the main limiting factors, rather than carbon dioxide concentration. Most of the accumulation will be in the atmosphere and in the ocean, with the ocean slowly losing its ability to absorb carbon dioxide as it becomes more acid. This is why the addition of carbon dioxide from combustion of fossil fuel (8.53 Gt CO_2- C in 2007) is so serious: this input, repeated year after year, will eventually increase atmospheric concentration by many times itself.

It has sometimes been argued that the annual release of fossil-derived carbon dioxide is of little importance because it so small relative to the total annual carbon flux between the atmosphere and the two great carbon pools, the land and the sea. Looked at in this way, it is indeed small: the release of fossil carbon in 2007 was only 4 % of the annual flux of 215 Gt C between the atmosphere, land plants and the ocean – see **Figure 2.2**. If the huge reserve of inorganic carbon in the oceans (about 40000 Gt DIC) exchanged rapidly with atmospheric carbon dioxide, an annual release of 8.53 Gt of fossil carbon would indeed matter little. But this argument is wrong, because it takes many centuries for carbon dioxide in the air to come to equilibrium with the inorganic carbon in the sea: meanwhile fossil-derived carbon dioxide builds up in the atmosphere.

Further reading for Chapter 2

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Chapter 3 – how people use energy

3.1 *Where the energy used by people comes from*

Nowadays about a third of our energy comes from oil, the next most important contributors being coal and natural gas (**Figure 3.1).**

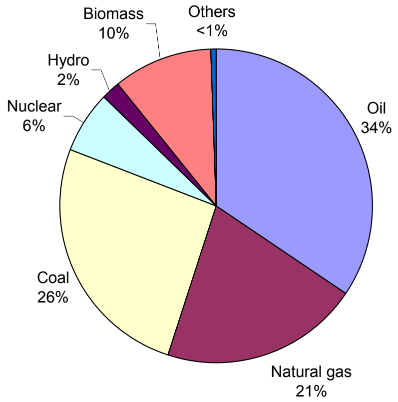

Figure 3.1 Where the energy used by people comes from

For 2006, based on International Energy Agency: *Key World Energy Statistics 2008*. Total primary energy supply (TPES, which includes energy lost during electricity generation, coal mining, etc.) was 4.92 x 10^{20} J or 11.74 x 10^9 tonnes oil equivalent (toe). 'Biomass' is wood, crop residues, animal waste, etc. used for fuel; 'Others' include geothermal, solar, wind, etc.

About 30 % of the energy used by people goes to industry, 25 % to transport and 30 % to residential use (**Figure 3.2**). By far the greatest part of the energy used by transport goes

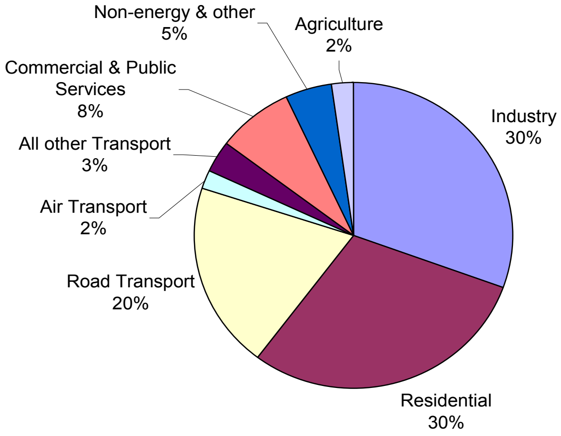

Figure 3.2 Where the energy used by people goes to, as % Total Final Consumption.

From www.earthtrends.wri.org, updated to 2006. The International Energy Agency publication *Key World Statistics 2008* gives Total Final Consumption (TFC) in 2006 as 3.38 x 10^{20} J or 8.084 x 10^9 tonnes oil equivalent (toe). TFC is the sum of consumption by the different end users, i.e. it excludes the various energy losses incurred prior to delivery. International Energy Agency: *Key World Statistics 2008* splits TFC in 2006 in a somewhat different way: 27 % was for the industry sector, 28 % for total transport, 36 % for 'other sectors' (a term which includes residential use, services and agriculture) and 9 % for non-energy use.

to roads, with airtransport accounting for only 2 %. Note that Total Primary Energy Supply (TPES: see legend to **Figure 3.1**) was 11.74 x 10^9 tonnes oil equivalent (toe) in 2006 and Total Final Consumption (TFC: see legend to **Figure 3.2**) was 8.084 x 10^9 toe in 2006: the difference is the energy dissipated in bringing TPES to the point of consumption.

On the global scale, coal is still the major fuel used for electricity generation, with natural gas well behind (**Figure 3.3**). Most electricity is generated in large plants, a typical modern coal-fired generating station producing 1-2 GW. Hydroelectricity accounts for one sixth of global production, with a tiny (2.3 %) contribution from wind and other renewable sources. The world electricity generating *capacity* was 4.0 TW in 2006, nearly twice that in actual use over the year (2.2 TW).

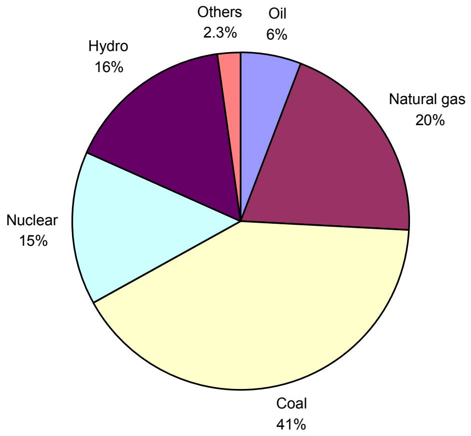

Figure 3.3 Where the energy used to generate electricity comes from.

For 2006, based on International Energy Agency: *Key World Energy Statistics 2008*. Total world production of electricity in 2006 was 18930 TWh. 'Others' include geothermal, solar, wind, combustible renewables and combustible waste.

Most of the older thermal generating plants convert about one third of the heat energy in the incoming fuel to electrical energy, but modern gas-fueled generators using combined cycle gas turbines are more efficient (**Table 3.1** and **Chapter 5.5**). Although this table is only for electricity production in the UK, it is typical for a country with a mix of generators of different ages using different fuels.

Table 3.1 also shows the quantities of carbon dioxide produced per kWh of electricity generated: modern gas-fired generators produce less than half the carbon dioxide per kWh of electricity generated than coal-fired plants. Coal and oil generators also produce sulfur dioxide, which costs money to remove from flue gases, if done at all. For 1 % sulfur in coal (most generating coals contain more), 4 g of SO_2-S is produced per kWh of electricity generated.

Table 3.1 The environmental cost of electricity production in the UK from different fuels[a]

	Units	Coal	Oil	Natural gas
Used in electricity generation	M tonnes	47.8	1.3	
Used in electricity generation	M tonnes oil equivalent (toe)	30.0	1.5	32.3
Energy content of fuel used[b]	TWh	348	20	377
Electricity supplied[c]	TWh	119	5	174
Generating efficiency	%	34	26	46
Carbon dioxide produced	g CO_2-C per kWh	248	194	107

[a] For 2008, based on Digest of UK Energy Statistics, 2009, Chapter 5

[b] Low heat of combustion - see Chapter 3.2

[c] Electrical energy produced, less that used in generation

3.2 *Combustion of fuels*

First of all, consider the heat evolved when some common fuels are burned.
(**a**) The combustion of carbon
$C\text{ (solid)} + O_2\text{ (gas)} \rightarrow CO_2\text{ (gas)}$
Heat is released by this reaction: in scientific terminology the enthalpy of combustion at 25 °C and a pressure of one atmosphere is -394 kJ mol^{-1}; in engineering units the heat of combustion is 32.8 MJ kg^{-1} (or 14100 BTU/lb since 1 kJ kg^{-1} = 0.430 BTU/lb). These (and the following) heats of combustion assume the same temperature (25 °C) and pressure (1 atmosphere) before and after the combustion – i.e. they are the fuel engineer's 'high' heats of combustion, when the steam is condensed to water.
(**b**) The combustion of hydrogen
$2H_2\text{ (gas)} + O_2\text{ (gas)} \rightarrow 2H_2O\text{ (liquid)} + 143\text{ MJ kg}^{-1}$
(**c**) The combustion of methane
$CH_4\text{ (gas)} + 2O_2\text{ (gas)} \rightarrow CO_2\text{ (gas)} + 2H_2O\text{ (liquid)} + 55.6\text{ MJ kg}^{-1}$
(**d**) The combustion of methanol
$2CH_3OH\text{ (liquid)} + 3O_2\text{ (gas)} \rightarrow 2CO_2\text{ (gas)} + 4H_2O\text{ (liquid)} + 22.7\text{ MJ kg}^{-1}$

The heat of combustion of coal is 17–34 MJ kg^{-1}, with anthracite at the high end: dry wood ~16 MJ kg^{-1}; crude oil ~ 33 MJ kg^{-1}; gasoline ~ 47 MJ kg^{-1}.

So far as energy production is concerned, hydrogen is by far the best fuel: burning a kilogram of hydrogen provides three times as much heat as burning a kilogram of gasoline. Burning a kilogram of pure carbon produces 32.8 MJ kg^{-1}, but 74.2 MJ kg^{-1} is produced if this kilogram of carbon is contained in methane. The four hydrogen atoms provide the extra heat when methane is burned – which is why hydrocarbons like gasoline have been described as convenient ways of packaging hydrogen. A kilogram of carbon in methanol (wood alcohol) gives rather less heat (60.5 MJ kg^{-1}) than a kilogram of carbon in methane (74.2 MJ kg^{-1}), because methanol is already part oxidized. Similarly, ethanol (ordinary alcohol: heat of combustion 24 MJ *per litre*) is a less productive fuel than gasoline (34 MJ per litre).

3.3 *Reserves of fossil fuels*

Table 3.2 gives the global annual consumption of oil, natural gas and coal, together with current estimates of the 'proved reserves' of these fuels. Coal alone accounts for two-thirds of the total 'Proved Reserves' of fossil carbon, oil for 20 % and natural gas for 14 %. If completely burned, these ‘proved reserves’ would consume about 0.16 % of the oxygen in the atmosphere. This Table also gives the time to exhaust ‘proved reserves’, assuming that no new reserves are discovered and that consumption continues at its present rate. These two assumptions will tend to balance out – consumption is likely to accelerate as more countries industrialize and it is unlikely that all the reserves have already been discovered.

Table 3.2 Global Fossil Fuel Consumption and Reserves

Fuel	Annual consumption in 2008[a] Gt toe	Annual consumption in 2008[b] Gt Carbon	Proved reserves at end of 2008[c] Gt Carbon	Time to exhaust proved reserves[a] years
Oil	**3.93**	**3.27**	**137[d]**	**42**
Natural gas	**2.73**	**1.64**	**99**	**60**
Coal	**3.30**	**3.51**	**428**	**122**
Total	**9.96**	**8.42**	**664**	

[a] British Petroleum. Statistical Review of World Energy 2009

[b] Calculated assuming oil produces 19.9 t C per TJ, natural gas 14.4 and coal 25.4, as given by ORNL.

[c] Calculated from time to exhaust proved reserves. Proved reserves are those that can be taken to be recoverable under existing economic and and operating conditions and that the rate of consumption in 2008 continues unchanged.

[d] Note there is an additional uncertainty about these figures, because the published oil reserves of certain important oil-producing countries bear little relationship to actual proved reserves, which are guarded as commercial secrets.

The total stock of reduced carbon in sedimentary rocks is of the order 10^7 Gt C, some 15000 times greater than the combined ‘proved reserves’ listed in **Table 3.2**. Most of this reduced carbon is present in such low concentrations that it is virtually inaccessible, but a small part is found at much higher concentrations in the oil-shales and oil-sands.

These oil shales and oil sands are mostly found in Canada, Venezuela and the North-Western USA, and are estimated to contain 400-500 Gt C of recoverable oil. As cheap readily-available energy reserves such as natural gas and liquid (i.e. pumpable) oil are used up, prices will rise, making it worthwhile to exploit resources such as the Alberta oil-shales and oil-sands, even though production costs are likely to be many times those for oil from (say) the Persian Gulf. At present, just over 1 % of the world consumption of oil (85 million barrels per day) comes from the bitumen held in tar sands. This oil is obtained by strip mining the tar–sand deposit and heating the crushed tar-sand with hot water to release the bitumen. The bitumen is then refined to give the desired oil. Production of carbon dioxide over the whole fuel cycle (i.e. ‘well to wheel’ production) from tar shales is likely to be 25 to 75 % higher than from conventional oil wells, the exact figure depending on the process used to extract and process the bitumen (Brandt et al. 2010. ACS: Oil shale: a solution to the liquid fuel dilemma). Methods for extracting bitumen by heating oil-sands and oil-shales *in situ* are being developed, thus avoiding the necessity for mining.

World demand for oil is forecast to rise from 12 Mt per day in 2007 to 15 Mt per day in 2030 (OECD/IEA, *World Energy Outlook*, 2008). There is no shortage of oil in the foreseeable future: according to the International Energy Agency, total reserves of conventional (i.e. pumpable) oil, oil from tar-sands, oil from oil-shales and extra-heavy oil contain roughly nine times as much oil as has been used by people up to now. The problem is the energy needed to extract and process the non-pumpable oil. As easily-got oil is used up, the cost of producing a barrel of oil will increase, as will the overall quantity of carbon dioxide produced when that barrel is used.

3.4 Emission of carbon dioxide from the combustion of fossil fuels

On the global scale, electricity generation accounts for 41 % of the carbon dioxide released to the atmosphere from fossil fuels, with transport coming second (**Figure 3.4**).

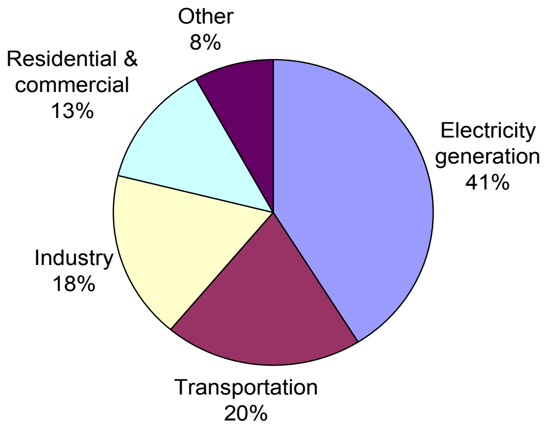

Figure 3.4. Carbon dioxide emissions from fossil fuel burning, by use, 2004.

Data from Earth Policy Institute/ Indicators/CO2/2008_data.htm

The emission of fossil carbon dioxide has increased relentlessly, year after year, with economic events like the great depression of the early 1930s causing no more than a temporary dip (**Figure 3.5:** fossil carbon emissions fell by 26 % between 1929 and 1932). The growth rate has accelerated recently, from 0.9 % per year over the period 1990-1999 to 3.5 % per year for 2000-2007, but may well fall again as the current economic depression takes hold. The International Energy Agency estimates that carbon emissions in 2009 will be 3 % less than in 2008.

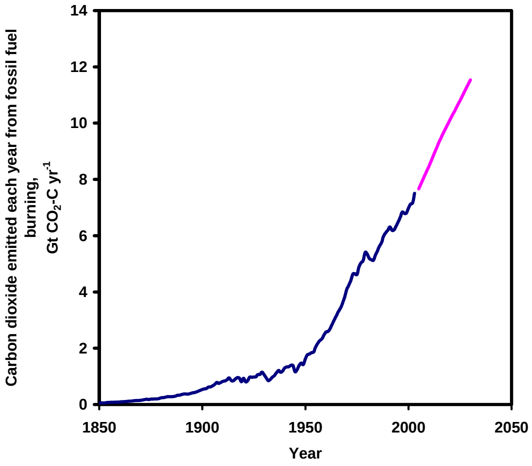

Figure 3.5 Global carbon dioxide emissions from combustion of fossil fuels.

The blue line shows data from Marland et al. 2007. Carbon dioxide Analysis Center, Oak Ridge National Laboratory for the period 1850-2004: the pink line shows the DOE/EIA 2008 projections for 2005-2030.

Figure 3.6 shows how the annual use of fossil carbon per person has changed over the last two centuries – and also the growth of the human population over this period. In contrast to the smooth population curve, the use curve reflects

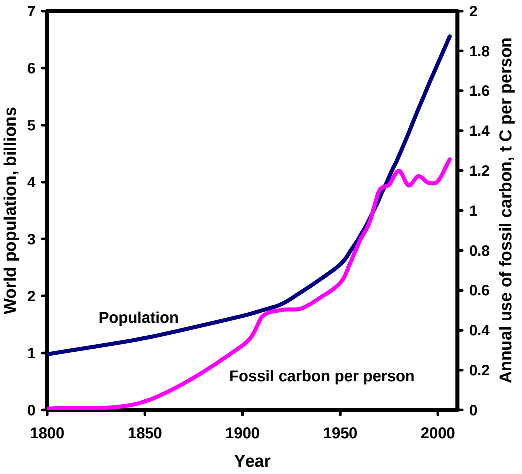

Figure 3.6 Growth of human population and quantity of fossil carbon used per person over the last two centuries.

Data from United Nations Population Division and Marland et al., 2007. Carbon dioxide Analysis Information Center, Oak Ridge National Laboratory.

the enormous economic changes in the twentieth century. Annual use of fossil carbon increased rapidly over the period 1850-1970, a rise broken only by the upheavals between 1914 and 1945. There was relatively little change between 1970 and 2000, mainly because the greatest population increase was then in the poorer parts of the world, where people use relatively little fossil fuel, masking its increased use in the richer parts. Another contributing factor was economic decline during the 1990s in the former USSR and in several other Eastern European countries. Since 2000 there has been a marked upward swing, as economic growth gains pace in India and China, increasing the demand for fossil fuel. This move towards a better standard of living in the poorer parts of the world is the single most important force driving global warming in the early twenty-first century. If the rest of the world used fossil fuel at the same rate per head as the USA in 2007, emissions of carbon dioxide from the burning of fossil fuels would increase by a factor of 5 - see **Table 3.3**.

3.5 Emission of fossil carbon dioxide per person

There is an extraordinary spread between the quantities of fossil carbon dioxide emitted per person in different parts of the world (**Table 3.3**). Per capita, a person living in the USA emits some three hundred times as much fossil carbon dioxide as one in the Democratic Republic of the Congo. Another surprising thing about this table is the difference

Table 3.3. Carbon dioxide emissions from fossil fuel burning by the 24 of the world's most populous countries[a]

Country	**Population in 2007**[b] millions	**CO_2 from fossil fuel burning in 2007**[c] tonnes CO_2-C per head
China	**1329**	**1.36**
India	**1169**	**0.37**
United States	**306**	**5.50**
Indonesia	**232**	**0.46**
Brazil	**192**	**0.54**
Pakistan	**164**	**0.24**
Bangladesh	**159**	**0.08**
Nigeria	**148**	**0.24**
Russian Federation	**142**	**3.12**
Japan	**128**	**2.71**
Mexico	**107**	**1.24**
Philippines	**88**	**0.25**
Viet Nam	**87**	**0.37**
Ethiopia	**83**	**0.03**
Germany	**83**	**2.53**
Egypt	**75**	**0.68**
Turkey	**75**	**0.99**
Iran	**71**	**1.91**
Thailand	**64**	**1.19**
Congo	**63**	**0.02**
France	**62**	**1.61**
UK	**61**	**2.53**
Italy	**59**	**2.05**
Myanmar	**49**	**0.06**
Rest of World	**1674**	**1.50**
WORLD	**6670**	**1.29**

[a] This Table is ordered by size of population, countries with the largest populations being at the top: the 24 countries in the Table account for 75 % of the world's people

[b] From UN Population Division, 2007

[c] From Marland, Boden & Andres, Carbon Dioxide Information Analysis Center, US Department of Energy 2007. Marland et al.'s data for 2004 updated to 2007, using BP Statistical Review of World Energy, June 2008

between France, on the one hand, and the UK on the other. With similar populations, a person living in France emits on average 1.61 tonnes CO2-C in one year, compared to 2.53 for the UK. This is because France generates a much greater portion of its electricity by nuclear fission.

Further reading for Chapter 3

Smil, Vaclav. 2008. *Energy in Nature and Society. General Energetics of Complex Systems*. The MIT Press.
How energy governs nature and civilization.

Smil, Vaclav. 2005. *Energy at the Crossroads. Global Perspectives and Uncertainties*. The MIT Press.
How people now use energy and how this might change.

MacKay, David. 2009. *Sustainable energy - without the hot air.* UTI.
This book, manly concerned with the UK, is highly critical of loose thinking and introduces an improved way of assessing and comparing energy strategies.

International Energy Agency: *Key World Energy Statistics, 2009.*

British Petroleum. *Statistical Review of World Energy, 2009.*

Chapter 4 - using models to forecast future climate

4.1 Modelling the future

Atmospheric-Ocean General Circulation Models (or AOGCMs) are the primary tools for assessing the effects of human activity on that complex system we know as climate. AOGCMs are constructed by linking two sub-models: one that represents the dynamics of the atmosphere (i.e. the movement of mass and energy through the global atmosphere), the other the dynamics of the ocean. They are usually tested by seeing how well they can account for past changes, before being used to forecast future changes. This process is illustrated in **Figure 4.1**, which shows how the measured changes in global temperature during the 20th century were used as a test of the output from a particular aggregation of models. It is immediately clear from **Figure 4.1** that the aggregated models can only account for the increase in temperature over the last three decades *if human activities are factored in*. It is also clear that this particular assembly of models is now sufficiently sophisticated to give a reasonably close account of changes over the whole century, suggesting that it is now good enough to give useful predictions over the next few decades.

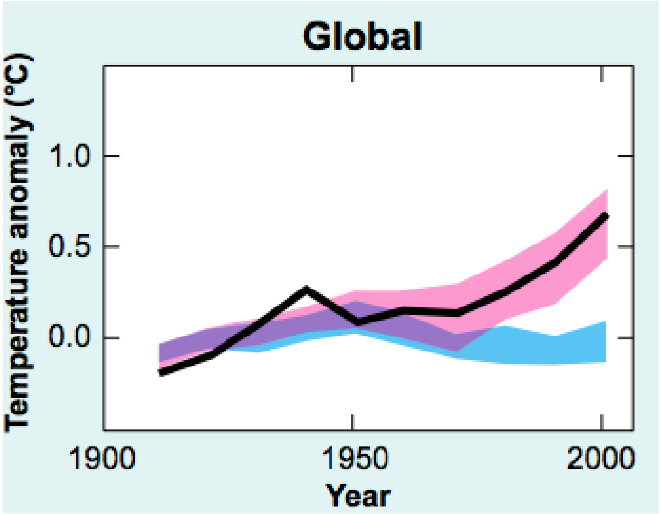

Figure 4.1 Global temperature anomaly as simulated by an aggregated set of models

Part of Figure TS. 22, IPCC, 2007: *Climate Change.* I. The black line shows the *measured* global mean temperature (plotted mid-decade) over the period 1906-2005, relative to the average for 1901-1950. The blue shaded band shows the 5-95% range for 19 simulations from 5 climate models, using *only* the natural forcings caused by solar activity and volcanoes. The red band shows the 5-95% range for 58 simulations from 14 climate models, using both natural *and* anthropogenic forcings.

4.2 Trajectories for the accumulation of greenhouse gases in the atmosphere

If an AOGCM is to be used to investigate how changes in greenhouse gases might affect future climate, it must first be primed with a representation of these changes. This can be done by extrapolating present trends into the future – for example the pink line in **Figure 3.5** shows how annual emissions of fossil carbon dioxide are projected to rise over the next two decades. Factors that might derail the extrapolation, such as economic recession or major political turmoil are ignored. Yet even this simple forecast is more complex than it looks: the trend is near-linear only because the forecast for the wealthier OECD (Organization for Economic Cooperation and Development) nations is a 14 % increase in emissions by 2030, compared to an 85 % increase by the non-OECD nations, which include China, India and Brazil.

Extrapolations such as that in **Figure 3.5** are useful for a decade or two, at most. For longer periods, it has been more usual to set up a suite of possible scenarios (or 'storylines') and then use these to prime the AOGCMs. Some years ago, the IPCC set up four socio-economic scenario 'families', termed A1, A2, B1 and B2 (for details, see the IPCC Special Report on Emission Scenarios, 2000). For example A2 is very much a 'business as usual' scenario, with uneven economic development across the world, rapid and uneven population growth, together with the slow and reluctant introduction of technological change. By contrast, the A1B scenario is for a world in which population growth peaks in mid-century, economic growth is rapid and more efficient technologies for energy supply and use are developed across the board, without particular stress on any one technology. Greenhouse gas emissions are calculated for each scenario and the resulting atmospheric concentrations used to drive the AOGCM.

There has been a move in recent years to drive models from a range of emission trajectories, rather than from the old IPCC scenarios (Hibbard et al. 2007. *Eos*, **88,** 217-221). One such trajectory could be a 1 % increase in CO_2e every year, where CO_2e is the sum of the concentrations of all the long-lived greenhouse gases, expressed as their carbon dioxide equivalent. Alternatively, present concentrations could follow a specified trajectory to an equilibrium level, say 450 ppm CO_2e, or perhaps more realistically, present concentrations could rise to a maximum, before falling away, again following a specified trajectory. The socio-economic conditions that would generate the selected trajectory are then worked out independently of the AOGCM. For an exploration of how emissions peaking in 2015, 2025 or 2035 influence global mean temperature, each for the same specified annual reduction rate, see the submission to the Poznan Conference by Parry et al. 2008, at http://www3.imperial.ac.uk/climatechange.

Another approach is to ignore trajectories altogether and simply consider the effects of a finite injection of greenhouse gases, without worrying too much about when these inputs occur. Recently, modelers have found that the relationship between cumulative emissions and peak warming is remarkably insensitive to just when the emissions occur. Thus Allen et al. calculated that if humans emitted a total of 1000Gt C, without specifying exactly when, the peak warming would be 2°C, with a 5-95% confidence limit of 1.3 - 3.9°C (Allen et al. *Nature.* 2009, **485**, 1163-1166). People have already released about half this: some 500 Gt C was emitted between 1850 and the present (see **Table 2.2**). At the current rate of release (some 9 Gt C per year) it would take just over fifty years to emit the next 500 Gt C: sooner if the rate of release continues to accelerate. Modelled in this way, humanity cannot emit more than a further 500 Gt C if warming is to be restricted to 2 °C. Ominously, proved reserves of fossil carbon in oil, gas and coal (at almost 700 Gt C: see **Table 3.2**) add up to more than this.

4.3 Modelled changes in temperature.

Figure 4.2 shows global surface temperatures over the next hundred years, as predicted by an assemblage of AOGCMs operating on three of the IPCC scenarios. The orange line shows predicted temperatures if the concentrations of the various greenhouse gases remained the same throughout the 21st century as in 2000. Temperatures continue to rise because of the gases already released in the 20th century. This rise is slow (about 0.4 °C during the 21st century), but inexorable, mainly because of the huge lags in the oceanic part of the system.

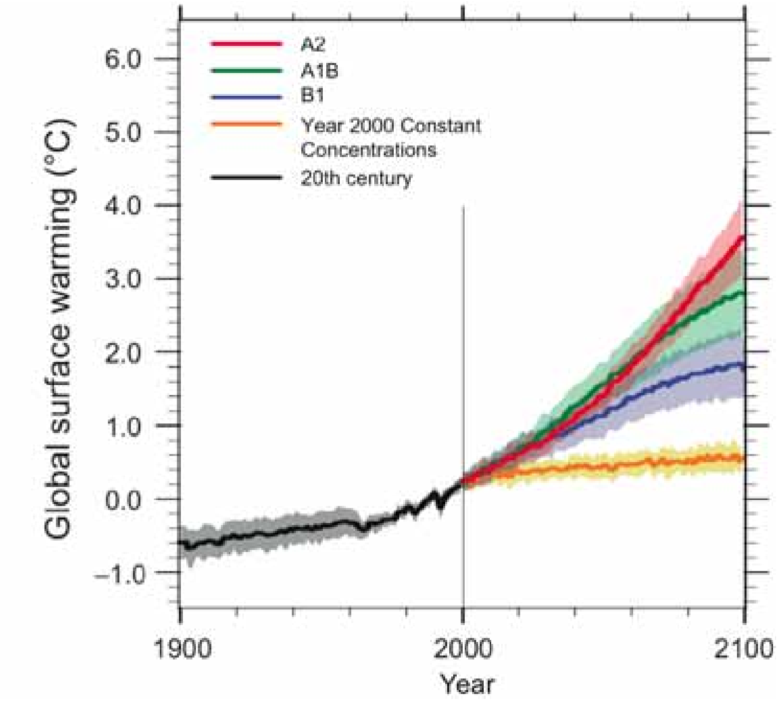

Figure 4.2 Global surface warming, as predicted for a range of scenarios

From Figure SPM.5, IPCC, 2007: *Climate Change.* I. The solid lines are multi-model global averages of surface warming (relative to 1980-1999) for three scenarios, shown as continuations of the 20th century simulations. Shading denotes ± one standard deviation range of individual model annual means.

The black line shows temperature throughout the 20th Century.
The orange line shows predicted temperatures if the concentrations of the various greenhouse gases stayed the same throughout the 21st century as in 2000.
Scenario A2 (red) is for a world in which population increases throughout the century and economic growth is uneven, uncoordinated and regionally orientated.
Scenario A1B (green) is for a world in which population growth peaks in mid-century, economic growth is rapid and more efficient technologies for energy supply and use are developed across the board, without particular stress on any one technology. Scenario B1 (blue) is for a world in which population growth peaks in mid-century, but with a rapid move away from heavy industry and the introduction of clean and efficient technologies

The red line is the 'business as usual' scenario (A2) in which population increases throughout the 21st century and economic growth continues in a regional and uncoordinated way, with no overall attempt to control greenhouse gas emissions: temperatures rise by 3.4 °C during the 21st century. The green (A1B) and blue (B1) scenarios illustrate how organized attempts to restrict population growth and control emissions could reduce warming, although even the best (B1) gave a temperature rise of 1.6 °C by 2100.

Figure 4.2 was contructed by aggregating the outputs from the best models that were available when the runs were done. More recent work with the Hadley Centre model alone (**Table 4.1**), which includes an updated carbon cycle sub-model, predicts an even greater rise for a ‘business as usual, no action taken’ scenario: 5.7 °C by 2100, compared to 4.2 °C from the A2 scenario in **Figure 4.2**. (Note that this 4.2 °C estimate is relative to the pre-industrial level, not to the 1980-1999 base line used in **Figure 4.2**, from which the rise is 3.6 °C). Of the four scenarios in **Table 4.1**, only one, in which emissions start to decrease in 2010 and reductions quickly reach 3 % per year, comes even near to holding the temperature rise to 2 °C. Under this particular scenario, the rise in global temperature by 2100 is between 2.1 °C (with a 50 % chance of occurring) and 2.8 °C (10 % chance). By 2050 emissions are a third of those in 2007 and continue to decline for the rest of the century.

Table 4.1 Predicted increases in global temperatures for four contrasting scenarios[a]

Scenario	**Greenhouse gas emissions in 2050, relative to that in 1990, which is set at 1**	**Predicted temperature rise by 2100, in °C above pre-industrial level**[b]	
		50 % chance of occurring	**10 % chance of occurring**
Early and rapid emission fall, starting 2010	**0.53**	**2.1**	**2.8**
Early but slow emission fall, starting 2010	**1**	**2.9**	**3.8**
Late and slow emissions fall, starting 2030	**1.76**	**4.0**	**5.2**
Business as usual - no action taken	**2.32**	**5.5**	**7.1**

[a] Based on data from V. Pope at www.metoffice.gov.uk/climatechange/.../action/evidence.html

[b] The pre-industrial level is 0.6°C below the 1980-1999 mean used in Figure 4.2

4.4 Modelled changes in precipitation

People flourish over a wide range of temperatures - but rainfall is a different matter. Overall, as mean global temperature increases, more water will evaporate from oceans and lakes, increasing the quantity circulating each year through the global hydrological cycle. However, all the current Atmospheric-Ocean General Circulation Models predict that there will be major changes to the distribution pattern. **Figure 4.3** shows how precipitation is predicted to change by the end of this century, as calculated by the assembly of models used by the IPCC in the 2007 Report. Increases in precipitation are very likely in high latitudes and in certain equatorial zones, while decreases are likely in most subtropical regions. For the A1B scenario (a world in which population growth peaks in mid-century, economic growth is rapid and more efficient technologies for energy supply and use are developed across the board, without particular stress on any one technology), the decrease in the subtropics is around 20 %. These predictions are in line with recent measurements of precipitation (see Stott et al. 2010. *Wiley Interdisciplinary Reviews: Climate Change*, DOI:10.1002/wcc.34).

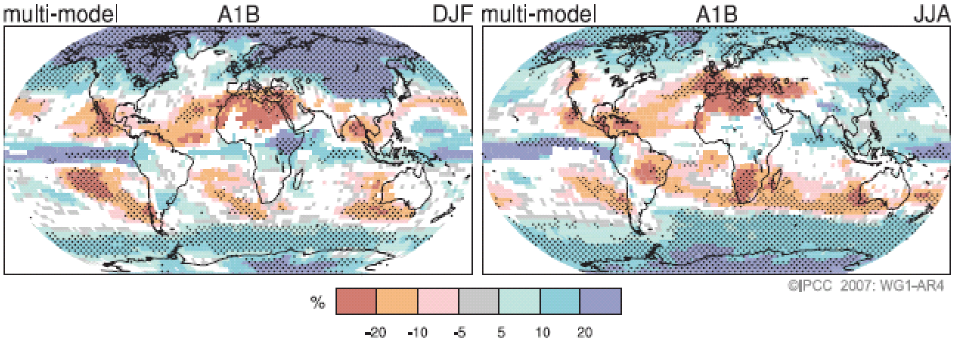

Figure 4.3 Projected changes in precipitation in 2090-2099, relative to precipitation in 1980-1999.

From Figure SPM.7, IPCC, 2007: *Climate Change.* I. Winter (December, January and February) on the left, summer (June, July and August) on the right. The predictions are multi-model averages for the A1B scenario – for details of this scenario see legend to Figure 4.2. White areas are where less than 66 % of the models agree on the sign of the change and stippled areas are where more than 90 % of the models agree on the sign of the change.

Predicting precipitation change is particularly difficult for modelers. For one thing, global warming will not cause temperatures to increase uniformly over the oceans, where most evaporation takes place (see for example Xie, et al. 2010. *J. Climate*, 23, 966-986) Local ocean surface temperatures are known to have a large influence on precipitation events such as the monsoon. Most (but not all) glaciers are currently in retreat, but as temperatures rise, causing more evaporation, snowfall may increase in certain areas, allowing glaciers to grow. Ice sheets are expected to increase in parts of Antarctic (**Figure 4.3**).

4.5 Modelled changes in sea level

Sea levels have risen by about 110 m since the last Glacial Maximum, roughly 20000 years ago (**Figure 1.9a)**. This rise was caused by the melting of ice sheets and had largely ceased 6000 years ago. However, land that has been pressed down by a mass of ice slowly rises once the ice melts, causing vertical land movements that still continue.

There was a small rise in sea level of about 0.16 m (IPCC, 2007: *Climate Change.* I, Figure TS.18) during the twentieth century, although it is not known how much of this rise was caused by human activities. An increase in global mean annual temperature would increase sea level by two main processes: by thermal expansion of oceanic water and by enhanced melting of glaciers, ice sheets and other land-borne ice. The thermal capacity of the ocean is so large that it would take centuries to come to a new equilibrium in response to a change in atmospheric temperatures, with deep water lagging far behind the more responsive mixed layer. During the twentieth century, the surface temperature of the oceans increased by a global mean of just under 0.8 ^{o}C (IPCC, 2007: *Climate Change.* I, Figure TS.22). Calculations (IPCC, 2007: *Climate Change.* I, Table SPM.1) suggest that about half the observed increase in sea level between 1993 and 2003 was due to thermal expansion.

Complete melting of the Greenland and Antarctic ice sheets would be catastrophic. If the Greenland sheet melted, sea levels would rise by 7 m and if this was followed by complete melting of the Antarctic ice sheet, sea levels would rise by a total of about 64 m (*Climate Change*, IPCC, 2007, 4.6.1). For comparison, complete melting of all the other glaciers and ice caps across the world would give a rise of only 0.2-0.4 m. Changes in floating sea ice will of course have a negligible effect on sea level. Under steady-state conditions, the annual input of snow to an ice sheet is balanced by the annual loss by melting and/or production of icebergs. The balance of these processes is different for the Greenland and Antarctic ice sheets. Antarctic temperatures are so low throughout the year that there is virtually no runoff of liquid water, so that ice is lost to floating ice shelves, which experience melting and refreezing on their underside, eventually breaking away as icebergs. By contrast, summer temperatures are now so high on the Greenland ice sheet that about half the annual loss is by melting, the other half by formation of icebergs. There is also recent evidence from Greenland that the outward ice flow is speeding up, possibly because of lubrication of the bottom of the glaciers by melt water.

Sea level changes track temperature closely over the last 400000 years (**Figure 1.9a**) and an ice-sheet response time of centuries seems probable, with changes of several metres per century possible, once wide-scale surface melt is underway (Hansen et al. 2007. *Phil. Trans. R. Soc. A.* **365**, 1925-1954). The increases in sea level caused by likely increases in global temperature are the subject of active research: calculations published three years ago (IPCC, 2007: *Climate Change*. I, Figure TS.27) suggested that sea levels will be 0.2 to 0.6 m higher by the end of the present century than at the beginning. However the latest (2009) report of the Scientific Committee on Antarctic Research (SCAR) estimates that sea levels will be 1.4 m higher by 2100, mainly because of the rapid warming of the Greenland ice-sheet and the loss of ice mass from Antarctica.

4.6 Modelled changes in thermohaline circulation

Recently there has been much debate about what would happen if global thermohaline circulation slowed or stopped. This is particularly important for Western Europe, because the Gulf Stream and its continuation, the North Atlantic Drift, both part of the global oceanic circulation, transport around 10^{15} W of heat northwards, making mean temperatures some 8°C higher in Western Europe than in the equivalent latitudes of North America. Changes in the prevailing winds could weaken the Gulf Stream, as could changes in the underlying thermohaline circulation. Thermohaline circulation could weaken if warming caused loss of sea ice from the regions round the North Pole, decreasing the production of dense salty water. Increased runoff from the great rivers that empty into the Arctic Ocean could also increase the flow of light fresh water, as could increased melting of the Greenland ice sheet.

When an ice age comes to an end, warming is sometimes punctuated by brief returns to colder conditions. These changes can be abrupt – a matter of a decade or so - and have been interpreted as the result of thermohaline shutdown, caused by the release of vast quantities of glacial melt water into the circumpolar oceans. Whether or not global warming will cause thermohaline shutdown in the North Atlantic (and elsewhere) depends, primarily, on the magnitude of forthcoming changes in temperature and in precipitation. The present consensus is that there is a real possibility that thermohaline *slowdown* may occur in the forthcoming century: none of the present models have shown a complete shutdown, or a net cooling over land areas (see Wood et al. 2006. In *Avoiding Dangerous Climate Change*, Ed. Schellnhuber et al., pp 49-54, Cambridge).

4.7 Modelled changes in extreme weather

Most AOGCMs predict that heat waves, with the increase in human mortality that is often associated with unaccustomed high temperatures, will become increasingly frequent if the rise in greenhouse gases is unchecked (IPCC, 2007: *Climate Change*. II, 8.2). Correspondingly, low temperature extremes are predicted to become less frequent. Both predictions are consistent with measurements over the last fifty years. An increase in extreme rainfall events is also predicted, with droughts becoming more irregular in duration and intensity, again in accord with observations in recent decades. The predictions for tropical storms are less consistent between models and observation, but some models suggest that tropical cyclones (typhoons and hurricanes) will become more intense, but possibly less frequent. It is very difficult to detect the impact of human activity on extreme weather events, because the occurrence of such events was always irregular, even before people started releasing greenhouse gases on a large scale. You need good data over a long period to detect meaningful changes in the occurrence of rare events.

4.8 Greeenhouse gas targets

There are three major problems in setting a maximum allowable (or target) concentration for greenhouse gases in the atmosphere. The first is scientific: to calculate the effect of a range of possible target concentrations on global temperature, rainfall distribution, sea level, oceanic circulation and so on. The second is sociological: to specify what level of damage is intolerable to human society. This is a particularly difficult issue - for example, a rise in sea level of a couple of metres, disastrous for people living on a coral atoll, would matter little to those living on high ground. Again, a small decrease in rainfall that would wipe out pastoral agriculture in semi-arid areas would be of little importance in wetter places. Indeed, a little warming might even be welcome to people living in high latitudes. The third is a political problem, to devise politically acceptable (and cost effective) ways to keep emissions below the chosen target. None of these problems is easy.

In 2007 the IPCC gave some provisional figures for calculating the temperature rise caused by specified concentrations of greenhouse gas, based on the models then available. Once equilibrium had been attained, a greenhouse gas concentration of 441 ppm CO_2e will cause a (best estimate) temperature rise of 2°C above the pre-industrial level, a concentration of 556 a rise of 3°C, a concentration of 701 a rise of 4°C and a concentration of 883 a rise of 5°C (IPCC, 2007: *Climate Change*. III, Table 3..9).

With each degree rise, the environmental damage – and the cost of meeting it – mount exponentially. Estimates of the direct and indirect damage arising from increases in temperature were set out by the IPCC in 2007 (IPCC, 2007: Climate Change. II, Table TS.3, later updated by Parry et al. Nature 2008, doi:10.1038/climate.2008.50) and the remainder of this paragraph is based on these sources. A rise of two degrees above the 1980-1999 level would increase food production in high latitudes, but decrease production in warm semi-arid areas. Extreme weather events, for example rainstorms so intense that they cause wide-scale flooding, would become more common. A 2-3 °C increase would see changes in oceanic circulation, with knock-on effects on North Atlantic temperatures and on monsoon rains, plus increased melting of the Greenland ice sheet, with the associated rise in sea level. Many animal and plant species would disappear from their present habitats. Extreme weather events would become ever more common. A 3-4 °C rise would, in addition to all these, cause almost complete melting of the Greenland and West Antarctic ice sheets, eventually resulting in a sea level rise of some 12 metres. Beyond 4°C predictions become increasingly uncertain, because of the positive and negative feedbacks that operate in the carbon cycle, in oceanic circulation, in the distribution of clouds and so on.

In 2005 the European Union committed itself to keeping the rise in global temperature to within 2°C of the pre-industrial level and specified that a target concentration of 450 ppm CO_2e would have a 50/50 chance of staying within this 2°C ceiling. However, it is almost certainly too late for a 2°C target - the total concentration of all long-lived greenhouse gases is now about 430 ppm CO_2e (of which 384 ppm was carbon dioxide in 2007 - and this rose at close to 2 ppm per year over the decade ending in 2007).

According to one report (*The Garnaut Climate Change Review*, 2008. Cambridge University Press, Australia), a 550 ppm CO_2e target may be the best that is politically realistic, despite the huge costs in adaptation and acclimatization that such a target would imply. According to this report 'achieving the objective of 450 ppm would imply tighter controls on emissions than now seem likely in the period to 2020. A 450 ppm objective would require an emissions reduction commitment by developed countries of …… around 5 % per year. The only alternative would be to impose even tighter constraints on developing countries from 2013, and that does not seem to be realistic at this time'. These conclusions are largely in accord with the latest report from the International Energy Agency, which concludes that the OECD countries *alone* cannot put the world onto the path to a 450 trajectory, even if they were to reduce their emissions to zero by 2030 (IEA World Energy Outlook 2008 Report).

At present it seems likely that concentrations are likely to overshoot a target of 450 ppm CO_2e before deep cuts in emissions can be brought to bear. A concentration of 550 ppm CO_2e means that society will have to brace itself for a temperature rise of about 3^oC (from the pre- industrial level) by the end of the present century, with all the attendant problems.

The AOGCMs used to calculate the response to a specified increase in the emission of greenhouse gases are undergoing rapid evolution, as more becomes known about the global climate system, particularly the various feedbacks, positive and negative, that operate. These feedbacks can lead to non-linear responses to change – the so-called 'tipping points'. As (say) atmospheric carbon dioxide concentrations increase, there will be, for a time, a proportional increase in global mean surface temperature, but at some 'tipping point' the climate system flips and goes into another state, where the previous proportionality no longer holds. Tipping points are notoriously difficult to model.

Although the models are improving, forecasting remains an uncertain trade and the further a forecast is projected into the future the more uncertain it gets. Yet it will not do to postpone action on climate change until better models are available – by the time they arrive, too much damage may already have been done. We have to work with the best of the models that we *now* have, constantly checking them against actual measurements as time unwinds - and modifying the models as necessary – see Schiermeier, (2010, *Nature*, **463**, 284-287) for a discussion of the problems facing current climate modelers. As models improve, so will our ability to construct realistic targets – and to specify what will happen if these targets are not met.

In the next four chapters I will examine various ways of reducing emissions of greenhouse gases – mitigation in the IPCC terminology, followed by a chapter on how people might adjust to a warmer world – adaptation in the jargon.

Further reading for Chapter 4

IPCC, 2007: *Climate Change*. I, particularly Chapters 8, 9 and 10.
Modelling the climate system, as it was in mid-decade.

McGuffie, K. and Henderson–Sellers, A. 2005. *A Climate Modelling Primer*. Third Ed. Wiley.
An introduction for students with no background in meteorological modelling.

National Research Council. 2002. *Abrupt Climate Change: Inevitable Surprises*. NRC, USA.
Worrying.

Walker, G. and King, D. 2008. *The Hot Topic*, Bloomsbury.
Particularly good on the effects of warming, degree by degree.

Stott, P.A. et al. 2010. *Detection and attribution of climate change: a regional perspective*.
Wiley Interdisciplinary Reviews: Climate Change.DOI:10.1002/wcc.34.
A review of recent developments, confirming and extending IPCC, 2007: *Climate Change*. I.

Chapter 5 – Reducing the release of greenhouse gases to the atmosphere

5.1 *Using energy more efficiently – the major losses*

Before considering individual ways of saving energy in detail, it is worth looking at a diagram (**Figure 5.1**) that shows the overall use of energy, but presented in a different way from **Figures 3.1, 3.2,** and **3.3**. The outstanding feature of **Figure 5.1** is its complexity – and it is immediately clear that no single – or simple - solution can exist for reducing energy flows.

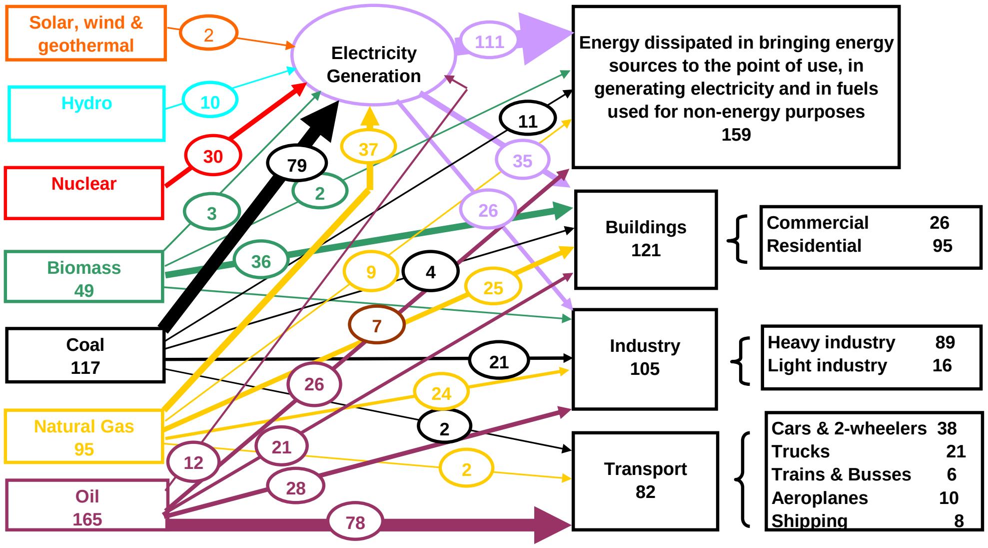

Figure 5.1 Energy flows in 2004 from human activities, in EJ (10^{18}J)

This diagram is a simplified version of Figure 4.4 in IPCC, 2007: *Climate Change*. III. The primary data used to construct the original Figure came from the International Energy Agency: Key World Energy Statistics 2006. Flows have been rounded up and flows of less than 1.5 EJ omitted.

In producing the 468 EJ used by humans in 2004, 2.89 Gt CO_2-C came from coal, 1.45 Gt from natural gas and 2.78 Gt from oil. A further 1.1 Gt came from biomass burning - mainly as fuel for cooking and heating in the poorest parts of the world - but this will have come from recent plant growth, at the expense of atmospheric carbon dioxide, and hence is largely carbon neutral (see **Chapter 7.1**). Almost a third of the total energy used in residential buildings comes from this biomass, which is one of the reasons why there is so great a difference between calculations based on International Energy Association statistics (95 EJ for *residential* buildings in 2004 – see **Figure 5.1**) and the US Energy Information Administration value for *residential* buildings of 50 EJ, also for 2004. The US Energy Information Administration data are based on *marketed* energy sources alone.

It is worth taking the data in **Figure 5.1** a little further, to see the effect that an arbitrary 5 EJ decrease in energy use would have on each of the end-use sectors. **Table 5.1** shows that a reduction of this size would cripple public transport, but would only demand a 5-

6 % reduction in energy use for residential buildings or by heavy industry. Although not strictly an energy end-use, a 5 EJ saving could also be achieved by a 5 % reduction in the energy dissipated during electricity generation. A saving of 5 EJ would necessitate a 13 % reduction of the energy used by cars and motorbikes, or a 19 % reduction by light industry. Clearly the biggest gains are to be had by increasing the efficiency in the electricity generating industry and by tackling waste by heavy industry and in residential buildings.

Table 5.1 Percentage reduction in energy use in different sectors of the world economy for a saving of 5 EJ.

Sector	**Reduction in energy consumption to achieve a saving of 5 EJ, as % of total use by each sector in 2004**
Commercial buildings	**19**
Residential buildings	**5**
Heavy industry	**6**
Light industry	**31**
Cars and motorbikes	**13**
Trucks	**24**
Trains and buses	**83**
Aeroplanes	**50**
Shipping	**63**
[Electricity generation losses]	**[5]**

In contrast with **Figure 3.2,** which is all about energy use, **Figure 5.2** shows the emission of greenhouse gases by the various sectors, in terms of their carbon dioxide equivalents. A sector such as agriculture, which barely appears as an energy consumer in **Figure 3.2**, is much more important as a generator of greenhouse gases. I shall now consider, sector by sector, how energy can be used more efficiently.

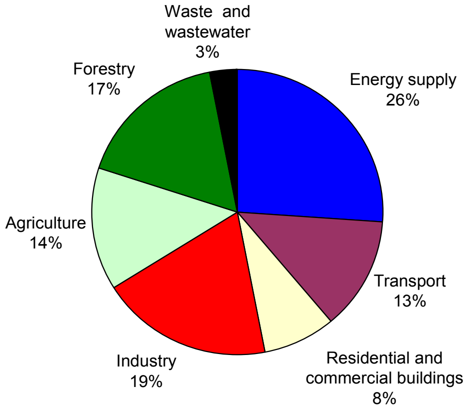

Figure 5.2 Greenhouse gas emissions by sector in 2004.

Redrawn from IPCC, 2007: *Climate Change*. III. Figure TS.2b.

5.2 *Using energy more efficiently - transport*

With some relatively minor exceptions, such as the loss of refrigerants from car air conditioners, or the production of nitrous oxide by internal combustion engines, the major greenhouse gas produced by modern transport is carbon dioxide. Combustion of fuel produces water vapour, a powerful greenhouse gas (see **Chapter 2.1**) – but in quantities vastly less than that already present in the troposphere. Only in the much drier stratosphere is water vapour from aircraft engines likely to have any appreciable influence. Aircraft contrails (made up of ice crystals) are a very visible form of pollution but even so have relatively little impact on climate – the IPCC puts radiative forcing from aircraft contrails at 0.01 Wm^{-2} (IPCC, 2007: *Climate Change*. I, Figure SMP.2).

Nowadays fossil carbon is by far the dominant source of energy for motor vehicles, airplanes, boats and trains. As more efficient ways of using this fossil fuel are developed, less carbon will be needed to move one person one kilometre. Fuel economy is rising – thus average fuel use by cars in the USA was 6.0 km per litre in 1974 and 12.2 in 2004, (excluding Sports Utility Vehicles, or SUVs, which currently do 5-7 km per litre) – but still far below what is currently available, for example 23 km per litre for one hybrid petrol/electric car in commercial production. More efficient engines, lower transmission losses, lower rolling friction, better aerodynamics, all contribute to better fuel use. However these gains are offset by the rapid rise in the number of vehicles – there are now some 0.8 billion motor vehicles in use, worldwide, consuming 14 % of the total energy supply used by humans (TPES, as in **Figure 3.1**), compared to a total of 0.48 billion in 1985. In the USA, there are now about 0.47 cars (excluding SUVs) per person, compared to 0.03 in China – although official Chinese sources expect this number to rise rapidly.

Some data (**Table 5.2**) from Great Britain illustrate the problem facing anyone trying to improve transport fuel efficiency: cars produce 31 g CO_2-C per passenger per km, more than trains (17 g) or buses (23 g), but much less than domestic aviation (69 g). Yet because

Table 5.2 Carbon dioxide production from passenger transport in Great Britain and USA in 2005

	Passengers carried[a]		**Energy consumed**[a]		**Carbon dioxide emitted**	
	Billion passenger kilometers		**M tonnes oil equivalent**		**g CO_2-C per passenger per kilometre**	
Passenger cars	**678**	**[4300]**	**24.8**	**[234]**	**31**	**[41]**
Buses and coaches	**48**	**[34]**	**1.3**	**[1.9]**	**23**	**[44]**
Trains	**52**	**[9]**	**1.0**[b]		**17**[b]	
Domestic aviation	**10**	**[940]**	**0.8**	**[47]**	**69**[c]	**[38]**

[a] From Department of Transport. Statistics Great Britain 2006

[b] Calculated from Association of Train Operating Companies. Energy Statement 2007

[c] Reference [b] gives 63

US data in [ ] calculated from US Dept Transport. National Transportation Statistics 2007

US passenger car data exclude SUVs

so many more passengers journey by car, a (say) 10 % improvement in this measure of efficiency saves vastly more fuel than a 10 % improvement in any of the other modes of transport in **Table 5.2**. The corresponding data for the USA, where population and distances are so much greater, show that passenger cars (excluding SUVs) use almost five times as much energy as all the other forms of passenger transport combined. It is worth noting that the sort of passenger cars used in the UK produce less carbon dioxide per passenger kilometre than those used in the USA, although for domestic air travel the situation is reversed, presumably because short flights are fuel inefficient. Although countries will differ in the proportions of travel by road, rail and air, the universal dominance of the private car in developed economies makes this a key sector for improvements in fuel efficiency.

Air is the most rapidly growing sector of the transport industry: in 2005 global passenger miles flown grew by 7 %, compared with a growth of 2 % in transport as a whole. Although only about 2 % of *worldwide* energy use (**Figure 3.2: TFC**) goes to aviation, in a developed country like the UK the figure is much larger (5.1 % of total UK energy consumption in 2005). Today's aircraft operate on some 30 % less fuel than those of 40 years ago and further improvements in fuel use, through better aerodynamics, more efficient engines and by reducing aircraft weight are anticipated. Aircraft have a much longer life (60 % of 30 year-old aircraft are still in service) than cars, whose average life is little more than a decade, so that improvements in efficiency are slower to emerge. Virtually all commercial aircraft fly on kerosene-type fuels, derived from petroleum, and it is difficult to envisage these fuels being replaced within the next couple of decades because of their high power-to-weight ratio. In the long run, oil prices will rise relative to other fuels, as oil reserves are exhausted, and aircraft fuel may then be made from biomass or from coal by the Fischer Tropsch process (see **Chapter 7.2**) – but aircraft could well be the last form of transport to move away from petroleum-based fuel.

Many ways of saving the energy used in transport are already available – for example by working from home using modern communication systems, rather than traveling to work, or by using virtual conferences, as an alternative to moving people across the world. In the more distant future, social changes such as organizing towns round public transport could minimize the need for private transport. Many of the mega-cities that have sprung up in the developing world over recent decades lack adequate public transport systems and their road systems are grid-locked for much of the day. Public urban transport could reduce both roadside pollution and the waste of fossil fuel in these mega cities.

5.3 Using energy more efficiently – buildings

The Intergovernmental Panel on Climate Change noted in its 2007 Working Group III Report that there are huge opportunities to use energy more efficiently in the built sector (the term 'built' being used for the combined residential and commercial sector) and, further, that energy saving in this sector (which accounts for 38 % of the Total Final Consumption (TFC) of energy by humans - see **Figure 3.2**) could be achieved more cheaply than in any of the other sectors examined in this Report, for example transport. Residential use dominates, accounting for 70 % of the total energy used by the 'built' sector. In 2004 the built sector emitted 2.3 Gt CO_2-C (including that released during the production of the electricity used by this sector) as CO_2 and a further 0.5 Gt of CO_2-C equivalents as N_2O, CH_4 and halocarbons. To quote the Report 'There is a broad array of accessible and cost-effective technologies and know-how that have not as yet been widely adopted, which can abate the emission of greenhouse gases by buildings to a significant extent. These include passive solar design (i.e. alignment of buildings relative to the Sun), high-efficiency lighting and appliances, highly efficient ventilation and cooling systems, solar water heaters, good insulation, high-reflectivity building materials and multiple glazing'. Domestic heating by electricity is very energy intensive, but the same quantity of heat can be obtained for much less electricity if a heat pump is installed – a reduction of three quarters has been claimed for the best installations. Heat pumps collect energy from outside the house – from a nearby stream, or, more usually, from pipes buried in the soil.

The largest potential savings in energy use (quoted in the IPCC, 2007: *Climate Change*. III Report as 75 % or higher) are only possible in new buildings that are designed and operated so as not to waste energy. However since the building stock turns over so slowly, the greatest short-term improvements must come by diminishing energy losses from existing buildings, through better insulation, less wasteful units for heating and air-conditioning and more efficient domestic appliances. An appreciable part of the energy used in domestic housing goes to water heating (for the UK, 25 % in 2000) and solar water-heating panels can reduce this, even in old houses. Particular attention needs to be given to cheap and efficient air-conditioning, if, as seems likely, the tropical and semi-tropical parts of the world become more prosperous.

Even relatively simple changes such as the replacement of incandescent light bulbs by lower-wattage fluorescent lights can have a significant saving Thus electric lighting presently produces 0.5 Gt CO_2-C per year, with a further 0.1 Gt coming from oil-based lighting, mainly used in the third world, a total emission that is 47 % of that from *all* road transport. According to the IPCC, electricity use by *domestic* lighting could be reduced by a factor of four to five by replacing incandescent and halogen lights and introducing occupancy sensors (IPCC, 2007: *Climate Change*. III, 6.4.9). Everyone in a factory, shop or school should be aware of the cost of energy – large energy meters, callibrated in the local currency and visble to all, might help.

5.4 Using energy more efficiently - industry

The IPCC stated that about 85 % of the energy used by the industrial sector goes to a group of energy–intensive trades, usually termed 'heavy industry' (IPCC, 2007: *Climate Change*. III, Chapter 7). These comprise the iron and steel industry, the non-ferrous metals industry, the manufacture of chemicals and fertilizers, the production of cement, lime, glass and ceramics, the refining of petroleum and the paper and wood pulp trade. In 2004 the whole industrial sector emitted some 3.2 Gt CO_2-C, of which 1.2 Gt was evolved during the production of the electricity used by the sector, 1.5 Gt from the energy needed for the manufacturing processes themselves and 0.5 Gt from non-energy uses of fossil and non-fossil fuels. A further 0.12 Gt (on a CO_2-C equivalent basis) was emitted from industry in the form of other greenhouse gases, notably halocarbons, sulfur hexafluoride, and nitrous oxide.

There are large differences in emissions and energy efficiency between new and old industrial facilities and the modernization of old factories and processes could decrease emissions considerably. According to the IPCC, the largest mitigation potentials per unit cost are in the steel industry, the cement industry and in the pulp and paper industry (IPCC, 2007: *Climate Change*. III, Chapter 7). By introducing 'Best Practice Commercial Technologies', i.e. technologies already available, the International Energy Agency calculated that the industries listed in **Table 5.3** could save over 300 mt CO2-C per year, 7 % of the total emission of fossil C by people in 2004. Taking the *upper* IEA estimates for energy savings (**Table 5.3** shows the *lower* estimates) the saving is 9 %. These are the 2004 savings: nowadays the opportunities are almost certainly greater.

Over the last twenty or thirty years heavy industry has moved more and more away from the original industrial countries, the USA, England, France, Germany, Japan, etc., to the developing countries, particularly China, India and Brazil. Thus Chinese raw steel production increased from 66 million tones in 1990 to 501 mt in 2008, with China now being the biggest

Table 5.3 Potential savings by adoption of Best Practice Technologies in heavy industry[a]

Industry	Energy saved EJ yr^{-1}	CO_2-C saved mt yr^{-1}	Energy saved, as % total used by each industry
Chemicals/petrochemicals	5	101	13
Iron and steel	2.3	60	9
Cement	2.5	131	28
Pulp and paper	1.3	14	15
Total	11.1	306	

[a] For 2004, from International Energy Agency. (2007). Tracking industrial energy efficiency and CO2 emissions. Note that these are the *low* IEA estimates: in all the industries the upper estimates are markedly higher

steel producer in the world, whereas production decreased slightly in the USA over the same period, from 92 mt in 1990 to 90 mt in 2008. Steel production is extremely energy intensive: approximately 0.5 tonne of CO2-C is produced in making one tonne of steel, so that about 8 % of the fossil carbon used by people in 2008 (global steel production 1330 mt) went to steel making.

As heavy industry moves to the developing countries, these are the places where efforts to improve efficiency and reduce carbon dioxide evolution will have most effect.

5.5 *Generating electricity more efficiently*

Figure 5.1 shows that 173 EJ of energy was used to produce 61 EJ of electrical energy in 2004, with an efficiency of 35 % and the production of 2.7 Gt CO_2-C from fossil fuels. This huge dissipation of energy might seem an obvious target for economy. However, the laws of thermodynamics say otherwise: the theoretical maximum efficiency (i.e. electrical energy output per unit energy input) of a coal-fired generating plant is about 60 %. Coal-fired generating stations operate on the Rankine cycle (**Figure 5.3**), in which steam is raised in a boiler heated by coal, expands through a turbine that drives a generator, is cooled and the water then pumped back to the boiler. In general, the greater the temperature difference between the input and output heat levels in a heat cycle, the greater the efficiency. Modern generating stations (with steam temperatures of up to 655 ^{o}C) can reach efficiencies of nearly 40 %, although older stations typically operate at efficiencies in the low thirties.

Higher efficiencies can be obtained from a combined cycle gas turbine (CCGT) plant, in which natural gas burning at temperatures of up to 1500 ^{o}C drives a turbine connected to a generator. The still-hot exhaust gases from the turbine are then used to raise steam and drive another generator using the conventional Rankine cycle. Most new power plants running on natural gas are combined cycle, with efficiencies around 50 %. Another way to decrease energy waste is by using the exhaust heat from electricity power stations (characteristically at temperatures of up to 100 °C) for domestic and commercial heating. However, for obvious reasons, most large electricity generating stations are situated well away from domestic dwellings, so this option to save electricity is rarely feasible. Gas-fueled power stations do not need to be as large or intrusive as coal-fueled, and it may be posssible to place them where the waste heat can be used for domestic heating.

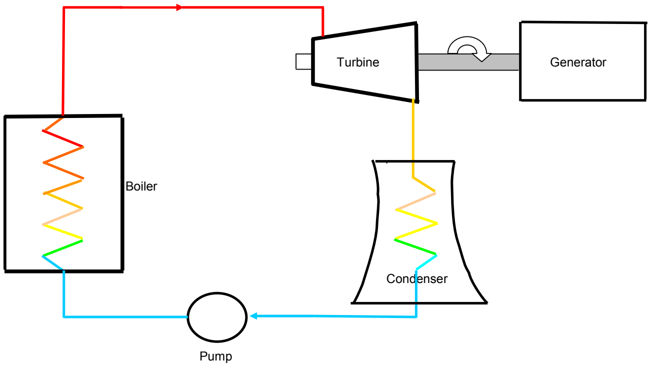

Figure 5.3 The Rankine cycle for electricity generation.

The fluid (normally water) is heated in the boiler, the steam drives the turbine, is condensed back to water in the condenser and the water pumped back to the boiler.

5.6 Capturing the carbon dioxide released by power stations and industry

Carbon dioxide capture and storage (CCS) is under active investigation as a way of reducing the release of carbon dioxide to the atmosphere. Electricity generating stations running on fossil fuel are an attractive target for CCS, since they now produce nearly 3 Gt CO_2-C every year and, being point sources, are intrinsically easier to deal with than distributed sources, such as private cars. However, the carbon dioxide in the flue gases from a conventional power plant is difficult to trap because it is greatly diluted with nitrogen from the air used to burn the fuel. Various ways to get round this problem have been proposed (see the IPCC Special Report *Carbon dioxide Capture and Storage*, 2005), but none are yet in operation on a large scale. One suggestion is to tackle the problem head on, by trapping the carbon dioxide in the flue gases chemically by reaction with bases such as ethanolamine (2-amino-1-ethanol) or ammonia. On heating the reaction product (possibly with steam), the carbon dioxide is released in a concentrated gas stream that can be compressed for disposal. Sorption in ethanolamine is already in small-scale use for the production of high-purity carbon dioxide – but huge absorption vessels would be needed to capture carbon dioxide from a full-scale electricity generating plant.

A second approach is pre-combustion removal in an Integrated Gasification Combined Cycle (IGCC) power plant. A coal slurry in water is first gasified in a limited supply of oxygen to syngas, a mixture of hydrogen and carbon monoxide. The carbon monoxide is then converted by the water-gas shift reaction to carbon dioxide and more hydrogen – for the chemical equations see **Chapter 7.2**. After removal of sulfur compounds, the carbon dioxide is separated (possibly by selective permeable membranes) from the hydrogen, which is then used to fuel a gas turbine.

A third possible approach is oxyfuel-combustion, in which oxygen rather than air is used to burn the fossil fuel. The heat generated is used to raise steam and drive a turbine in the usual way. Unlike combustion in air, the flue gases contain little nitrogen, so that it should be possible to capture the carbon dioxide from the dried flue gases by compression.

Trapping of carbon dioxide would have to be combined with permanent disposal of the trapped gas. One possibility for disposal is burial in deep impermeable rock formations - as already done in certain oil fields - if enough such formations can be found, within reasonable distances of the sources. The technology for this is not new: one million tones of carbon dioxide have been pumped into the Norwegian Sleipner oilfield every year since 1996. The gas from this oilfield contains much carbon dioxide, which is stripped from the raw gas and returned to the sandstone layer from whence it came. Another possibility is to liquefy the carbon dioxide and pump it to the bottom of the deep ocean (>3000 m), where, being more dense than sea water at this depth, it (or its hydrate) would form a pool. Hopefully the carbon dioxide in this pool would take many centuries to reappear in the mixed layer. In high concentration, carbon dioxide is a dense asphyxiating gas and, wherever stored, people would have to be persuaded that it would stay put.

The technical problems that still have to be solved if CCS is to be widely used are formidable. A 1000 MW generating station using pulverized coal and operating at a load factor of 80 % consumes some 2.5 million tonnes of coal in a year and produces about 7×10^9 kWh of electricity, emitting 6 million tonnes of carbon dioxide in the process. Huge amounts of energy would be needed to needed to trap, transport and dispose of this quantity of carbon dioxide. This energy would have to come from somewhere – presumably coal – in turn producing more carbon dioxide.

To sequester just 25% of the carbon dioxide emitted in 2005 by large stationary sources of the gas would require a disposal system with an annual throughput (by volume) slightly more than twice that of the world's crude oil industry (Smil, V. 2008. Nature, **453**, 154). Anyone proposing CCS as a significant way of reducing the egress of fossil carbon dioxide to the atmosphere will have to show, firstly, that CCS is technically feasible on the industrial scale and secondly, that CCS does not destroy the profitability of the process to which it is linked. If CCS is to be viable commercially, it will have to be heavily subsidized, either directly, or by means of a substantial carbon tax on competing generating plants that release carbon dioxide directly to the atmosphere.

5.7 Reducing the release of greenhouse gases by agriculture

Agriculture consumes only about 2 % of the energy used by humans (as % of TFC; see **Figure 3.2**) – although this figure does not include the energy in feed for draught animals in the poorer parts of the world. A small portion of this 2 % goes on fuel for machinery, but most on fertilizer manufacture, which produces about 0.15 Gt CO_2-C per year.

Soil organic carbon usually declines when woodland or grassland is brought under the plough, rapidly at first, followed by a slower decline that continues for years. On the other hand, improved agricultural techniques often lead to an increase in soil organic carbon. The present view (and it is not firmly based, see IPCC, 2007: *Climate Change*. III, Chapter 8) is that these processes are in approximate balance, with little net change in the flux of carbon into and out of agriculture. Whether this balance will be maintained in a warming world, with increasing temperatures favouring the more rapid breakdown of soil organic carbon, is another matter.

Improved agricultural techniques, such as the elimination of dry-land bare fallow (i.e. keeping the soil bare for a year so that enough water accumulates to grow a crop in the following year), could protect soil organic carbon that would otherwise be mineralized to carbon dioxide. Zero tillage, a cultivation system which avoids inversion ploughing, can reduce carbon loss from soils in some circumstances, but often makes little difference to the *total* soil stock of organic matter in a soil, merely leaving more on the surface and less at depth. The drainage of swamps rich in organic matter exposes this organic matter to biological oxidation, leading to the evolution of much carbon dioxide. Although such organic soils are often highly productive when drained, their potential for producing carbon dioxide formation needs to be considered before extensive drainage programmes are initiated. Careful management of the water table can mitigate the decomposition of organic matter in drained organic soils by keeping only the surface layer aerobic.

However by far the greatest contributions from agriculture to greenhouse gas emissions come, not from carbon dioxide, but from nitrous oxide and methane, both of which are products of anaerobic microbial processes – see **Chapter 2.10** and **2.14**. Calculated on a CO_2-C equivalent basis (from data in Chapter 8, IPCC, 2007: *Climate Change*. III), the production of nitrous oxide from agriculture in 2005 was equivalent to 0.8 Gt CO_2-C per year and methane 0.9 Gt, quite significant quantities compared to an emission in 2005 of 7.9 Gt CO_2-C from fossil fuels. Unlike point sources of carbon dioxide such as large electricity generating plants, agricultural emissions of nitrous oxide and methane are widespread and come from a range of different farming systems, so that they are likely to be more difficult to control.

According to the IPCC (see previous reference), agriculture was responsible for about 50 % of the methane produced by humans. The two main agricultural sources of methane are animal digestion and anaerobic soils, particularly paddy rice: neither source is easy to control with present knowledge. Careful manipulation of water level throughout the growing season can minimize the release of methane from paddy soils, as can, under certain circumstances, the use of ammonium sulfate rather than urea as nitrogen fertilizer. It may be possible to develop rice varieties that require less time under water to give an acceptable yield.

Ruminants now account for about a quarter of anthropogenic methane production (see *iaea.org/nafa/.../2008-atmospheric-**methane**.html*). The anaerobic phase of ruminant digestion evolved to utilize carbohydrates that are otherwise indigestible and methane appears to be an unavoidable byproduct of this process, with the methane being released fore and aft, from both ends of the animal's digestive tract. Various ways of reducing methane production by ruminants are being investigated, for example by changing the diet, or by altering the rumen microflora.

About 60 % of the nitrous oxide produced by humans comes from agriculture (IPCC, 2007: *Climate Change*. III, Chapter 8). As nitrous oxide is formed under anaerobic conditions (see **Chapter 2.14**), fertilizers, whether organic or inorganic, should preferably not be applied when soils are wet or waterlogged – or if heavy rain is forecast immediately after application. Emissions of nitrous oxide can be reduced by using no more fertilizer nitrogen than the crop requires, by timing application to plant demand and, possibly, by the use of nitrification inhibitors so as to retain nitrogen in the ammonium form.

As populations increase and people become more sophisticated in their tastes (for example by demanding a diet that contains more animal protein), each hectare of agricultural land will have to produce more food. Some of the nitrogen required to do this could well come from legumes that fix their own nitrogen, particularly in improved pastures. However the main food crops are wheat, maize and rice, all crops that need large quantities of fertilizer nitrogen, making it particularly important that this nitrogen be used efficiently and in a way that minimizes the evolution of nitrous oxide. World grain production was 2.3 billion tones in 2007, containing some 40 million tones of nitrogen: as the need for grain increases, so the need for nitrogen will increase in direct proportion.

5.8 Reduce the clearance of woodland

In 2005, trees contained 250-300 Gt carbon in an area of 40 M km^2, which is about 30 % of the world's land area, excluding Greenland and Antarctica. In contrast to the agricultural sector, carbon dioxide is the only greenhouse gas of significance emitted by the forest sector.

Nowadays, most forest clearance is for agriculture, but some is also cleared for settlements, roads and logging. Satellite observations show that 0.27 M km^2 of tropical rainforest was cleared in the six years 2000- 2005, an annual mean of 0.05. Most of the clearance is in the tropics and subtropics, but this is partially offset by increases elsewhere, the net decline in forest area being about 0.07 M km^2 per year (FAO Global Forest Resources Assessment, 2006), with a net annual decline in carbon stock of a little over 1 Gt C per year.

Increasing populations (and changes in diet as people become richer) will almost certainly insure that forest clearance for agriculture will continue in the tropics and subtropics, whatever incentives to stop are offered. Logging is a different matter and policies that stop wanton destruction of unwanted tree species and ensure replacement planting could reduce carbon losses **-** if properly policed. Indeed a properly-run forestry policy is sustainable in the long run, with tree felling in balance with new plantings. Carbon in paper or firewood can be out of circulation for several years; that in timber for decades or longer.

In many parts of the world, reforestation is actively encouraged – see **Chapter 6.2**. This can be on land that is no longer needed for agriculture, as in parts of northeastern USA, or on land that should never have been cleared for agriculture, allowing erosion to develop, as in parts of southwest China and Central America.

Further reading for Chapter 5

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Kreith, F., & Goswami, D.Y. 2007. *Handbook of Energy efficiency and renewable Energy*. CRC Press.
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Science, 2009. **325,** 1641-1652. Special issue: Carbon Capture and Sequestration.
Carbon sequestration and how it might be done.

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Not yet in print but prepublication available on line.

Chapter 6 – Geoengineering as a way of counteracting climate change

6.1 *Geoengineering*

The term Geoengineering is used to cover proposals to mitigate global warming by deliberately modifying the Earth's energy balance. These proposals fall into two very different groups

1. The direct removal of carbon dioxide from the atmosphere, thus reducing the greenhouse effect. In turn this can be subdivided into biological removal – for example by planting trees or by ocean fertilization – and chemical removal, for example by absorbing carbon dioxide on alkalis.

2. Reducing the incoming short- wave radiation reaching the Earth from the Sun, either by blocking sunlight on its way to the Earth or by increasing albedo, say by putting reflectors on the surface of the planet.

6.2 *Biological sequestration of carbon dioxide*

Carbon dioxide can be removed from the atmosphere by increasing its uptake by terrestrial vegetation, for example by planting trees on land that is not already forested. In one long-term experiment in England, an old arable site that had been allowed to revert to mixed deciduous woodland accumulated 236 t C per hectare in trees (above and below-ground), litter, and soil over a period of 118 years, during which time the carbon dioxide in the atmosphere above each hectare increased by 3.2 t CO_2-C ha^{-1} (Poulton et al. 2003. *Global Change Biology*, **9**, 942-955). Although the annual rate of uptake increased slightly over the 118 years on this particular site, eventually any forest will mature and there will be no net accumulation of carbon. At this stage, the annual loss of carbon from plant respiration, soil respiration and litter respiration is equal to that fixed by photosynthesis. Nevertheless trees are a net sink for carbon dioxide for many decades after planting. Land newly-planted to trees will also accumulate organic carbon in the soil – but only if the trees are planted on land that has been cultivated for many years – as in the example just quoted. Replanting trees on a forest site that has just been felled will only cause a temporary dip in soil carbon. When a wood is felled, the timber burned for fuel and the soil returned to arable agriculture, you are back where you started – so far as atmospheric carbon dioxide is concerned.

Afforestation is a viable option for carbon sequestration only when there is a surplus of land that is sufficiently warm and has enough rain to grow trees. If *all* of the world's rain-fed cropland (see **Figure 9.1**) was returned to forest (and much of it is too dry for high forest, for example the Kansas wheatlands) and if this forest gained carbon at the rate of the English site mentioned above (a mean of 2.0 t C ha^{-1} yr^{-1} over the whole 118 year period), then just under 30 % of the current annual production of fossil carbon dioxide could be sequestered. Surplus land, whether rain-fed cropland or pasture with enough rain to support trees, will become harder to find as population and food demand increase. But tree planting may gain time until people have developed methods for producing energy that do not release fossil carbon dioxide. Extensive changes in forest cover could have other effects on global warming. If the forests of Canada and Russia extend further northwards as a result of warming, the Earth's albedo will decrease, because trees reflect less light than ice and snow. Such a decrease in albedo would allow more solar radiation to be absorbed, giving a positive temperature feedback: conversely, extensive forest clearance in the tropics could lead to a negative feedback.

It is worth remembering from that, between 2000 and 2007, land uptake of carbon was greater than that released by forest clearance by very approximately 1.1 Gt C per year (**Table 2.2)**. World consumption of nitrogen fertilizer was 97 Mt N in 2006 and this nitrogen will allow greater uptake of carbon dioxide by plants, as will warmer summer temperatures in high northern latitudes. So will reversion of unwanted cultivated land to scrub woodland in places such as New England or the mountainous parts of central Italy.

In the long run, all the carbon taken up by a plant is released as carbon dioxide when the plant dies and decays, so that there is no net removal of carbon dioxide from the atmosphere (see **Chapter 2.4**). Various ways of preventing plant carbon from decay have been proposed, for example by dumping timber in the cold oceanic depths. Another is to make biochar, by heating plant material in insufficient oxygen for complete combustion. Lump charcoal can survive almost indefinitely in soil, so, assuming biochar is similar in stability, it could persist for much longer than the humic substances normally formed when plants decompose. Soil organic matter (SOM), which is mainly made up of humic substances, has a mean turnover time of about three decades in moist temperate climates and a decade or so in the humid tropics. The biochar would be incorporated in the topsoil, where it would improve porosity in heavy soils and perhaps increase retention of certain nutrients in light soils.

Though biochar can be made from virtually any plant debris, attention is currently focused on residues from agricultural crops. The global production of grain in 2007 was 2.3 Gt. If *all* the above-ground crop residues (straw, chaff, etc.) were harvested and used to make charcoal and if the mass of dry crop residues was the same as that of the grain, a generous estimate, about 0.4 Gt of biochar could be made - just under 5 % of the global evolution of fossil CO_2-C in 2007. Furthermore, the carbon expended in collecting and transporting these crop residues to where the biochar is made (and then taking it to where it is to be used) would have to be deducted from this 0.4 Gt.

Although most attention has been given to sequestration of atmospheric carbon dioxide on land, it has been argued that oceanic processes could also be used. Plankton growth is sometimes limited by lack of certain critical elements, notably nitrogen, phosphorus and iron. By supplying a growth-limiting nutrient at the right time and place, it might be possible to increase the sequestration of carbon by plankton. Iron is particularly attractive as an additive because it is needed by plankton in much smaller quantities than either nitrogen or phosphorus. Where iron is the limiting nutrient, for example in equatorial parts of the ocean that are far from inputs of terrestrial dust, additions of iron have been observed to produce a transient increase in phytoplankton. However, current calculations suggest that very little planktonic carbon sinks to the abyss and is taken out of the active carbon cycle: presumably the same would apply to any extra plankton produced by oceanic fertilization. If the annual net primary production (NPP) of the world's oceans is taken as 52 G t C yr^{-1} (see **Table 2.1**), then only some 0.2 G t C yr^{-1} is permanently deposited as organic matter on the ocean floor (see **Chapter 2.5**). The rest is rapidly returned to circulation, as the short-lived plankton die and are decomposed to dissolved inorganic carbon (DIC).

6.3 Chemical sequestration of carbon dioxide

Carbon dioxide can be removed chemically from the atmosphere - lime cement hardens when the basic calcium hydroxide it contains reacts with the acidic carbon dioxide in the air. However the same quantity of carbon dioxide had already been released in the manufacture of the calcium hydroxide from calcium carbonate (plus a little more from the fuel needed to burn the limestone), so nothing is gained in terms of the carbon cycle – unless the carbon dioxide released when the limestone is heated is disposed of by CCS.

Carbon dioxide is sequestered naturally during the weathering of silicate rocks, leading to the formation of calcium and other metal carbonates, which eventually accumulate on the sea floor – but this is an extremely slow process. Current estimates put this at less than 0.1 G t C yr^{-1}. People have suggested that carbon dioxide be removed from the atmosphere by mining basic rocks (such as basalt or peridodite), finely grinding them and exposing the powder to the air. For example, fosterite (a basic mineral belonging to the olivine group of silicates) slowly reacts with carbon dioxide:

$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$

Although this chemical reaction in itself is exothermic, the whole process almost certainly needs too much energy for it to be economic - for one thing, 1.6 tonnes of ground fosterite would be required to absorb 1 tonne of carbon dioxide. However basic (or better, ultrabasic) rock that has already been mined and ground, for example in mine tailings, might sequester useful amounts of carbon dioxide from flue gases.

Another possible approach is to react chalk with carbon dioxide and discharge the resulting calcium bicarbonate solution into the sea, where it would join the vast pool of inorganic carbon already there.

$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$

Presumably air would be bubbled through a slurry of chalk suspended in a stream of water, the bicarbonate being carried away in the aqueous outflow. Again, large quantities of chalk would be needed; 2.3 tonnes of pulverized chalk per tonne of carbon dioxide. This is the same process that leads to the formation of caves in limestone, although the concentration of carbon dioxide in the percolating water is much higher than that of water in equilibrium with air.

Other proposals are based on blowing air through organic bases such as ethanolamine. The trapped carbon dioxide is then displaced (a process that requires an external energy supply) and the original trapping agent reconstituted. The displaced carbon dioxide, either as the pure gas or as liquid under pressure, is then piped to a suitable geological site for long-term underground storage. Ion-exchange resins, arranged to present the maximum surface for absorption, could also be used – as in Lackner's Artificial Trees (for which see Lackner and Brennan. 2009. *Climatic Change*. DOI 10.1007/s10584-009-9632-0). The carbon dioxide trapped by the 'trees' would be chemically displaced and the pure gas (or liquid) piped away for storage – but see **Chapter 5.6** for the problems with storage.

Because carbon dioxide is well mixed in the atmosphere, all these chemical processes (and the biological processes described in **Chapter 6.2**) have one virtue in common: they trap carbon dioxide from wherever it is emitted, whether from cars, aircraft, electricity generating plants, or whatever. The chemical processes require less land than the biological and have an additional advantage in that they can be sited near the necessary rocks, or, in the case of sorption on basic chemical reagents, near the carbon dioxide burial site. However any chemical method that concentrates carbon dioxide from the level found in air to that suitable for burial involves a decrease in entropy and hence requires an external source of energy. It is therefore likely that the cost of removing carbon dioxide from the atmosphere by chemical methods will be greater per tonne of carbon dioxide than the cost of preventing fossil carbon dioxide from ever getting into the atmosphere, say by fitting CCS to coal-fired electricity generating stations. However chemical removal might come into its own if the world was presented with a catastrophic concentration of carbon dioxide in the atmosphere – but nobody has yet built an industrial-scale plant for removing carbon dioxide from the atmosphere, still less worked out how to dispose of it.

6.4 Reducing the incoming radiation reaching the Earth

A rough calculation shows that about 1.5 % of the incoming solar radiation would have to be blocked to compensate for a doubling of the carbon dioxide concentration of the atmosphere. A doubling of carbon dioxide from the pre-industrial level would cause a forcing of 5.35 ln(556/278) = 5.35 ln2 = 3.7 Wm^{-2} (see **Chapter 1.6**). Now the incoming solar radiation is 342 Wm^{-2}, which gives a long-wave outflow of 240 Wm^{-2} from the Earth (see **Figure 1.5)**. A doubling of carbon dioxide would increase this outflow to 243.7 Wm^{-2}. To return this to the pre-industrial level, the overall incoming radiation would have to be reduced to 342x240/243.7, or by just over 1.5 %.

Proposals for reducing the amount of solar radiation reaching the Earth fall into two main groups. The first is to place reflectors in near-Earth orbits – one proposal is to place 55,000 mirrors, each 100 m^2, in random orbit, another to place 2 billion tonnes of dust particles in equatorial orbit. The other way to reduce solar radiation is to place sunshades near the L1 point, where the gravitational pull of the Sun and Earth are equal. The L1 point lies on the line between the Sun and Earth, some 1.5 M km from the Earth and a sunshade of some 2 Mkm^2 would be needed to give a reduction of 1.5 %. Quite apart from the expense and feasibility, all these methods are subject to the objection that, should they not be maintained for any reason, the Earth would rapidly warm. According to *Geoengineering the Climate* (Royal Society, 2009) the various space-based methods are at so early a stage in their development, and their R & D costs so high relative to the other proposed ways of achieving radiative cooling, 'that they are unlikely to be feasible in the medium term'.

6.5 Increasing the reflection of solar radiation by the surface of the Earth

About 102 Wm^{-2} of the incoming solar radiation is reflected from the Earth (see **Figure 1.5**), giving an overall albedo for the planet of 102/342 or 0.298. To cool the Earth by 3.7 Wm^{-2} (**Chapter 6.4**), albedo would have to increase to (102 + 3.7)/342 or 0.309. Now from **Figure 1.5** the incoming radiation reflected by the atmosphere (clouds and other aerosols) is 79 Wm^{-2} and that absorbed by the atmosphere is 74 Wm^{-2}. If the increase in albedo was to come exclusively from the *atmosphere,* the mean atmospheric albedo would have to increase from 79/(79 + 74) or 0.516, to (79 + 3.7)/(79 + 74) or 0.528, an increase of 4.7 %. Of the solar energy reaching the Earth's *surface* (i.e. land and oceans), 23 Wm^{-2} is reflected and 167 Wm^{-2} absorbed (again see **Figure 1.5**). If the increase in albedo was to come exclusively from the *surface*, it would have to increase from 23/(23 + 167) or 0.121, to (23 + 3.7)/(23 + 167) or 0.141, a much larger increase of 17 %. Moreover, the oceans, which cover some 71 % of the Earth's surface, are comparatively poor reflectors, with an albedo of about 0.1. It is difficult to see how oceanic albedo could be significantly increased by human effort, implying that land albedo would have to increase by much more than 17 % to achieve a cooling of 3.7 Wm^{-2}.

Among the proposals for increasing land albedo are painting roofs and other urban surfaces white, covering large areas of desert with highly reflective surfaces and altering the reflectivity of vegetation. Estimates of the urban area that could be brightened range from 0.05 to 1 % of the land surface of the Earth, but even taking the larger figure, the radiative cooling would only be about -0.2 Wm^{-2} and this would be extremely expensive to attain and maintain (Royal Society. *Geoengineering the Climate*. 2009). Albedo could also be increased by covering suitable hot deserts with reflective films made of aluminized polyethylene, or some such material. Although this could meet roughly half the desired -3.7 Wm^{-2} of radiative cooling (Lenton and Vaughan. 2009. *Atmos. Chem.Phys. Discuss*. **9**, 1-50, a reference that takes a quantitative look at many of the geoengineering options), the cost of creating and maintaining a film that covers some 10 % of the Earth's surface would amount to several trillion US$ per year. To put this sum in proportion, it would take a carbon tax of $120 on every tonne of fossil carbon burned (taking the 2007 figure for fossil carbon use) to raise a trillion US$.

Altering the albedo of crops and grasssland vegetation has also been proposed as a way of countering global warming. Quite apart from the difficulty of re-engineering crops to be more reflective without at the same time reducing yields, a huge area would have to be engineered, for a relatively small change in radiative forcing – for estimates see the previous reference.

6.6 Increasing the reflection of solar radiation by the atmosphere

One way of increasing the reflection of solar radiation is to increase cloud albedo, particularly by whitening the low-level marine clouds that cover some one quarter of the ocean surface, mainly off the west coasts of North America, South America and Africa. All these areas are relatively dust-free and so have relatively few condensation nuclei to initiate cloud formation. An increase in the number of cloud condensation nuclei in the troposphere would allow more (and smaller) water droplets to form from a given mass of moist air. The more and the smaller the droplets, the more the incident sunlight is scattered, increasing albedo. Several ways of doing this have been proposed. If a fine spray of sea water is squirted into air unsaturated with water vapour, the water in the spray evaporates, leaving hygroscopic air-bourn salt particles. Air turbulence will carry at least some of these particles to heights where they could provide cloud condensation nuclei. Fleets of wind-powered ocean-going ships, each equipped with pumps to spray a mist of sea water into the air, have been proposed as one way of getting enough salt particles high into the cloud-forming zone. For more about the technique, its feasibility and its disadvantages, see the articles by Latham et al. and by Salter et al. (2008. *Phil. Trans. Roy. Soc. A.* **366**, 3969-3987 and 3989-4006, respectively), where it is calculated that a fleet of 1500 vessels could give a global forcing of -3.7 Wm $^{-2}$. Alternatively, a fleet of low-flying aircraft might be used to deliver cloud condensation nuclei to the cloud base, where the air is normally supersaturated with water vapour.

Another possible way of increasing cloud albedo is to deliberately place aerosols in the stratosphere. Size is critical: to scatter short-wave radiation in the visible part of the spectrum the aerosol particles must be no more than a few tenths of a micron in size. Larger particles scatter outgoing long-wave radiation and so could contribute to the greenhouse effect. Aerosols in the stratosphere persist for a time measured in years, in contrast to the tropospheric salt particles considered in the previous paragraph, which would be rained out in a matter of days. All sorts of materials have been proposed as stratospheric aerosols, but up to now sulfate has received most attention (Rasch et al. 2008. Phil. Trans. Roy. Soc. A. 366, 4007-4037). Sulfate (in the form of sulfuric acid) is unlikely to be used on its own, but would be formed *in situ* from one of a suite of sulfur-containing gases. Sulfur dioxide (SO_2), hydrogen sulfide (H_2S) and carbonyl sulfide (COS, the principal biological input of sulfur to the atmosphere) are all oxidized to sulfuric acid in the stratosphere. The sulfuric acid then aggregates with water to form an aerosol – see **Chapter 2.20**. The phenomenon is well known: large volcanic eruptions inject sulfur dioxide into the stratosphere, increasing the sulfate aerosol concentration and contributing to a cooling that can last several years. The opening of the Laki fissure in Iceland in June 1783 released roughly 120 Mt of sulfur dioxide into the atmosphere and was followed by a series of exceptionally cold winters in the Northern Hemisphere.

Calculations (see Royal Society. 2009. *Geoengineering the Climate*) suggest that between 1 and 5 Mt S yr^{-1}would be have to be injected into the stratosphere to have the desired effect, much less than the input to the *lower* atmosphere from industry, which averaged 63 Mt S yr^{-1}

over the decade 1991-2000. All sorts of ways have been proposed to put the required quantity of sulfur into the stratosphere, among them aircraft, artillery, balloons and rockets. The cost, effectiveness and long-term consequences, particularly on rainfall distribution, are as yet unknown – but need to be thoroughly investigated (see Keith et al. 2010. *Nature*, **463**, 426-427) before sulfur dioxide is proclaimed as a panacea for global warming.

Of all the geoengineering possibilities discussed in this chapter, the only one that is immediately available is afforestation of land now under crops or pasture – and this, at best, could only mop up a small part of the annual input of fossil carbon dioxide to the atmosphere. The others need extensive feasibility studies, followed by research and development into the most promising, all of which could be extremely expensive and take a long time. Trapping of carbon dioxide already in the atmosphere is energy intensive and requires safe long-term sequestration of the trapped carbon dioxide. Methods based on the deflection of sunlight before it reaches the Earth's atmosphere or on the reflection of sunlight from the Earth all have the disadvantage that carbon dioxide continues to build up in the atmosphere, with the attendant problem of ocean acidification. Deflection and reflection methods have the additional disadvantage that, should they fail for any reason, the excess carbon dioxide is still in the atmosphere and global warming would rapidly resume.

Further reading for Chapter 6

Royal Society. 2008. *Phil. Trans. Roy. Soc. A* Geoscale engineering to avert dangerous climate change. Special issue. **366**, 3841-4056.

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Chapter 7 – Energy from biomass

7.1 Replacing fossil carbon by carbon from contemporary biomass

One approach for reducing the release of fossil carbon dioxide to the atmosphere is to grow crops that are then used as fuel, either directly by burning the biomass itself, or indirectly, by conversion to useable liquid fuel. In theory this is carbon neutral, in that the carbon dioxide released during combustion merely replaces that removed from the atmosphere by photosynthesis some months or years earlier. In practice, any fossil carbon used to plant, fertilize, harvest, and process the biomass makes the process less than carbon neutral. There are two issues here: is the fossil energy required to grow and process the biomass more than can be saved from its use and if it is, can enough biomass be grown to replace an appreciable part of the demand for fossil energy.

7.2 The direct use of whole biomass as fuel

The direct use of biomass for fuel is of course not new – most poor people in developing countries still depend on biomass in one form or another. Biomass fuels now provide almost 1 % of global electricity, but the main use, some two thirds of the total, is for heating and cooking in poor countries. Smoke from burning biomass is a major cause of respiratory disease in the tropics, with women hunched over badly-ventilated cooking fires. More widespread use of biomass in industrialized countries will depend on how much it costs to grow, harvest and transport a low energy (a kg of wood has half the heating value of a kg of crude oil: see **Chapter 3.2**) and bulky material to the point of use. The trade in pelleted wood –which can be used industrially or domestically as fuel – has increased hugely over the last decade, amounting to about 4 Mt C in 2006.

Biomass becomes a more attractive option if grown on agricultural land that is not currently in use, less attractive if the land is taken from food production, which will tend to increase the cost of food. If plants are to be used as a source of liquid (or gaseous) fuels, the long-term solution may be to synthesise fuels from the *whole* plant, lignins included, by the Fischer-Tropsch process or something similar. The plant material, preferably one from a quick-growing crop that requires little fertilizer nitrogen (coppiced willow, eucalyptus or a grass like miscanthus), would first be heated at high temperatures and pressures to yield syngas (a mixture of carbon monoxide and hydrogen), which can then be polymerized by Fischer-Tropsch synthesis to give a range of hydrocarbon oils. The formation of syngas can be represented as

$C + H_2O \rightarrow H_2 + CO$

This is an endothermic reaction (i.e. it requires heat to drive it) and the energy is usually provided by an accompanying exothermic reaction, in which some of the biomass carbon is burned in insufficient air for complete combustion

$2C + O_2 \rightarrow 2CO$

More hydrogen can then be generated from the carbon monoxide by the endothermic water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$

The resulting syngas can then be catalytically converted to a range of hydrocarbons. For example, hexane can be formed

$13H_2 + 6CO \rightarrow C_6H_{14} + 6H_2O$

although it would be only one of many hydrocarbons formed during the reaction.

There are problems (for a review of these see Wang et al. 2008. *Biomass and Bioenergy*, **32**, 573-581) in making hydrocarbons from biomass: plant ash can sinter on the reactor walls during the production of the syngas; tar and other contaminants must be removed before the syngas reaches the catalysts that polymerize it to hydrocarbons. An alternative process uses anaerobic microorganisms to form ethanol from the syngas - yields of over 300 kg of ethanol per tonne of dry carbonaceous waste have been claimed. The char remaining from the gasification step could be used as an organic soil amendment – see **Chapter 6.2**

For many years, methane has been directly generated from plants by anaerobic fermentation in sealed containers, although again the energy needed to collect the plant material, keep the digester warm and dispose of the spent waste, must be allowed for. Almost any wet plant or animal material can be used, although things like farmyard manure or pig slurry, which are already partly decomposed, produce less methane per unit of incoming carbon. The biogas typically contains 50-70 % of methane, most of the remainder being carbon dioxide, plus a little gaseous nitrogen. The spent waste contains the lignin and some of the cellulose. Temperature, pH, feedstock and time spent in the digester must be carefully controlled and the successful running of a large biogas plant requires great skill.

7.3 Biofuels from plant constituents

Liquid fuels for transport are presently made from specific parts of plants: for example, ethanol by fermentation of the sugar extracted from sugarcane, or biodiesel from the oil extracted from oilseed crops. Consider the production of diesel fuel by methylating the oil from oilseed rape. A typical rape crop in the UK produces 3.25 t ha^{-1} of seed, giving about 1400 litres of oil. Once methylated, this quantity of oil will fuel 1.3 motorists for one year, assuming that the average motorist running a diesel car in the UK drives 15000 km in a year, with a diesel consumption of 14 km per litre (40 miles per UK gallon). The total area of land under crops and set-aside in the UK is some 5 M ha – enough to supply diesel for 6.5 million motorists for a year if all this land was allocated to permanent oilseed rape - but there were 26 million licensed private cars in the UK at the end of 2006. Likewise, it has been calculated that only 12 % of the gasoline used in one year in the USA could be done without if the *whole* corn (maize) crop was used to produce ethanol.

There is much confusion about how much fossil carbon can be saved by biofuels. At best, only a part of the carbon fixed by the crop can replace fossil carbon (**Figure 7.1**). Some carbon is needed to convert the desired part of the crop into commercial fuel (shown as light green in **Figure 7.1**) and in certain cases a portion of this carbon can come from the unused part of the crop. For example bagasse - the part of the sugarcane left when the sugar has been extracted – can be used to fuel a bioethanol factory. In this case the sector representing unused plant carbon (shown as pale yellow) decreases, in turn increasing the quantity of fossil carbon saved (purple sector) by growing biofuel. The unused plant material can either decompose in the soil, or part of it can be used to feed animals, for example the oilseed meal left after the oil has been removed can be used in cattle food. In either case the ultimate end product is carbon dioxide and there is no net saving of fossil carbon.

Calculations by Crutzen et al. (2008. *Atmos. Chem. Phys.* **8,** 389-395) indicate that the release of nitrous oxide (298 times more powerful as a greenhouse gas than carbon dioxide - see **Table 1.1**) can be so large for heavily-fertilized crops such as oilseed rape or maize that there is no net saving of fossil carbon from the production of biofuels. (In **Figure 7.1** the orange sector represents this effect). The position is more favourable for crops such as sugarcane, a plant that fixes much more carbon per hectare per year than oilseed rape, at the same time requiring less nitrogen. The average yield of Brazilian sugarcane is about 80 t dry

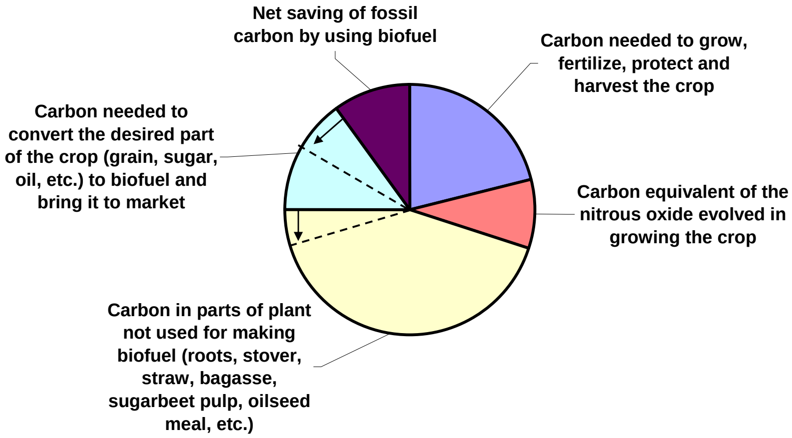

Figure 7.1 Diagram illustrating the carbon balance when a biofuel is made from part of a crop (sugar cane, grain, oilseed rape, etc).

The complete circle represents the carbon fixed by the crop in one year. The arrows show how the net saving of fossil fuel increases if part of the unused plant carbon (pale yellow) is used in the manufacture of the biofuel – for example if bagasse is used to fuel a bioethanol factory. Note that this diagram is for a field already under cultivation – carbon released if the land had first to be cleared is disregarded.

matter per hectare, producing some 7500 litres ethanol per hectare, or 3 t ethanol C ha^{-1}. Ethanol is an effective fuel for vehicles, although delivering less energy per litre (see **Chapter 3.2**).

Figure 7.1 shows that only limited replacement of fossil carbon is possible when the biomass crop is grown on unused agricultural land. Even less – if any – replacement is possible if the land has first to be cleared from forest or native grassland, liberating the carbon held in trees and soil as carbon dioxide. The very worst case is when organic (peat) soils have to be cleared and drained before the biomass crop is planted, as is happening in certain oil palm plantations in South-East Asia. The carbon dioxide released when the peat is exposed to air and begins to decay will far outweigh any saving of fossil carbon.

Certain organisms present in the herbivore rumen and in the termite gut can hydrolyse cellulose, the commonest constituent of plants, to its constituent sugar glucose (see **Chapter 2.7**). This might lead to a cheap source of bioethanol, if the enzymes involved in the hydrolysis could be made to work on a commercial scale and the resulting sugars fermented to ethanol. There are difficulties: all the higher plants also contain lignin and hemicellulose and these can interfere with the enzymic hydrolysis of cellulose.

Another approach to replacing fossil carbon is to grow algae (microalgae, not seaweeds) in shallow tanks of water exposed to sunlight and then process the lipids in the algae to give a biofuel. Like the higher plants, algae require nitrogen, phosphorus, potassium, and micronutrients, as well as carbon dioxide – indeed it has been suggested that algal farms be established wherever flue gases containing carbon dioxide are available. Many types of algae have been tested and the best can give oil yields, on a kg oil per hectare basis, greater than that from any crop growing in soil, even oil palm, which can an annual yield of up to 6 tonnes of oil per hectare. Algal cultures may well become important in sunny parts of the world, not only as sources of biofuels, but as human and animal feedstocks. However algal culture on an industrial scale is not easy, particularly because wild species can outgrow a desired high-yielding variety. There are also technical problems in maintaining optimal growing conditions – light only penetrates a few cm in a thick algal soup - and in harvesting. One calculation (Klöck, 2010. *Chemistry & Industry*, No.4, 27) indicates that, with present technology, at least as much energy is needed to grow, harvest, dry and extract the oil from dry microalgal biomass as the 27 MJ kg^{-1} of energy contained in this dry biomass. On the positive side, algae growing in tanks, troughs or tubes in sunny deserts would not compete with traditional food crops for land, although the area required would be considerable, because sunlight is so spread out – see **Chapter 8.7**.

As long as mineral oil is cheap, it is unlikely that *unsubsidized* biofuels will supply more than a small fraction of the fuel needed for transport - only in countries like Brazil, with large reserves of land suitable for growing sugarcane, are they likely to replace traditional vehicle fuels on a significant scale – indeed Brazil produced 25 billion litres of ethanol in 2008, supplying about half its gasoline requirement. In the future, people may regard biomass *burning* as a waste of valuable resource that could be better used as a feedstock for the chemical industry, for transport, pharmaceuticals, building material and so on.

Further reading for Chapter 7

FAO. 2008. *The State of Food and Agriculture 2008. Biofuels: Prospects, Risks and Opportunities*. Food and Agriculture Organization of the United Nations, Rome.

The role of Biomass in America's Energy Future. *Biofuels, Bioproducts and Biorefining*, 2009. Special issue. **3,** 105-288.

Reviews on biomass processing, mainly of switchgrass.
Clark, J.H. and Deswarte, F.E.I.. 2008. *Introduction to Chemicals from Biomass*. Wiley.

Science, 2009. **326**, 1344-1346. Exchange of letters on opportunities for and drawbacks of biofuels.

Chapter 8 - sources of energy that do not depend on carbon

8.1 Developing sources of energy that do not depend on carbon as fuel

Here the main aim is to generate energy without using fossil fuels – for a detailed assessment of the opportunities, see the special issue on energy published by the Royal Society (*Phil.Trans. Roy. Soc. A.* 2007. **365**, No.1853: also *Nature* **454**, 14 August, 2008). There are four main possibilities: atomic energy, whether from fission or fusion; solar energy, tidal energy and geothermal energy. Solar radiation can be used directly, for example in photovoltaic cells, or indirectly, because it is the ultimate source of wave energy, wind energy and hydroelectricity.

8.2 Nuclear energy from fission

When an atom of a fissile heavy element, usually uranium-235, is struck by a neutron (denoted by the symbol n), the atom disintegrates, forming two or more lighter elements and releasing heat and further neutrons in the process. This can be represented by the equation

$235U + n \rightarrow 236U \rightarrow 89Kr + 144Ba + 3n + \text{energy}$

although this particular pathway is only one of many that occur. The products, krypton-89 and barium-144, are themselves radioactive and undergo further decomposition. The energy comes from the conversion of mass to energy, the final (or rest) mass of the products being less than that of the reactants. The neutrons released during fission then go on to break up further atoms of uranium-235 in what is called a chain reaction. In a nuclear reactor this chain reaction is controlled so that heat is generated at a steady rate, the heat thus produced being used (directly or indirectly) to raise steam, which then drives a turbine connected to an electricity generator in the conventional way. Natural uranium contains only 0.7 % of the fissile 235 isotope and reactors for power generation customarily operate on uranium enriched to about 3 %.

In 2005, nearly five hundred nuclear power plants, many of them ageing, produced 15 % of the world's electricity (Figure 3.3) and the replacement of old plants and construction of new ones is under active debate. Like modern coal-fired generating plants, nuclear power plants tend to be large, producing 1GW or thereabouts. Nuclear power plants are best run at or near their nominal capacity and are therefore particularly suitable for baseload supply to national grids.

Nuclear fission produces the least carbon dioxide of all the *industrial* processes now in use for generating electricity. Some carbon dioxide is of course released during the manufacture of the steel, cement, etc. used in the construction of the reactor – and more during the mining and manufacture of the reactor fuel. A report by the OECD Nuclear Energy Agency (Nuclear Energy and the Kyoto Protocol, 2002) calculated that the total lifetime release of carbon dioxide from a gas-fired electricity generating plant was 105 g CO_2-C per kWh, compared to a release of 3-6 g CO_2-C per kWh from a nuclear power plant. This calculation included the energy used in mining the (high grade) uranium ore, in the isotopic enrichment of the uranium and in the construction and running of the generating plant.

A nuclear power plant costs much more than a gas plant with the same output, but, once built, fuel costs are much more important for the gas plant. Thus an advanced pressurized water nuclear reactor (EPR) would take longer to build and cost about three times as much as a gas combined-cycle plant (see *The Economics of Nuclear Power*. WNA, 2009). The cost of electricity from different sources is compared in **Table 8.1,** which lists the unit cost of electricity for five different kinds of power station. These costs include the capital cost of the generating plant and equipment, the cost of fuel burned (if applicable) and the cost of operating and maintaining the power station. The capital cost for nuclear plant includes an allowance for the costs of decommissioning. With no carbon levy (see **Chapter 10.1**), gas is cheaper than nuclear, but with a carbon levy of £30 per tonne of carbon dioxide emitted, the advantage is the other way round.

Table 8.1 Cost of generating electricity in different ways[a]

Power source	**Cost with no carbon levy**	**Cost with carbon levy at £30 per tonne carbon dioxide**
	UK pence per kWh	
Gas-fired combined cycle gas turbine (CCGT) plant	**2.2**	**3.3**
Nuclear fission plant	**2.3**	**2.3**
Coal -fired pulverised-fuel (PF) steam plant	**2.5**	**5.0**
Coal-fired integrated gasification combined cycle (IGCC) pl	**3.2**	**5.2**
Onshore wind farm[b]	**3.7**	**3.7**

[a] **From *The Cost of Generating Electricity*, Royal Academy of Engineering, 2004. For updates on some of these costs, see IEA. 2008. Energy Technology Prespectives.**

[b] **Excluding cost of standby power plants**

Although uranium is not a particularity rare element, being more common than tin, high-grade ores are limited, with one estimate of proved and probable reserves in present mines being only 5 Mt. Breeder reactors, which produce the fissile element plutonium-239 from the non-fissile uranium-238 in the course of operation, can in theory extract about 50 times more energy from uranium than ordinary thermal reactors. The plutonium is recovered from the spent fuel and can be reused to generate more heat - or it can be diverted to make illicit nuclear weapons, with all the problems that can then arise. Three steps are required for a successful breeder reactor: irradiation of the uranium-238 in a nuclear reactor; reprocessing of the spent fuel and manufacture of new fuel elements from the plutonium. No-one has yet succeeded in putting all three together.

Thorium, which is about three times more abundant than uranium, can also be used as a reactor fuel - although it is not fissile by itself. It occurs in nature as thorium-232, which can absorb a slow neutron in a reactor:

$^{232}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}\mathrm{Pa} + \beta \rightarrow {}^{233}\mathrm{U} + \beta$

to give uranium-233, which is fissile. In one design, a blanket of thorium surrounds a core containing U-235, which supplies neutrons to the subcritical blanket. The U-233 produced in the blanket is burned there - or could be extracted and used separately. Thorium is potentially better than uranium, because all of the mined element can be used, whereas only 0.7 % of mined uranium is the fissile uranium-235. Thorium has been extensively researched as a replacement for uranium as a reactor fuel, but has not yet been used commercially to generate electricity. The reasons are largely economic, but there are also problems in handling the highly radioactive decay products of the thorium cycle.

Spent fuel from nuclear reactors is customarily kept under water for at least three to five years, so that short-lived radioactivity can decay, the water being both a radiation shield and a means of keeping the fuel elements cool. The spent fuel is then put in containers and transferred to a storage facility, usually on or near ground level, where it can be kept securely - a process usually called storage. Storage is at best a temporary solution for radioactive elements with half-lives in the many thousands of years (for example, the plutonium-239 found in spent fuel has a half-life of 24000 years) and it is likely that permanent disposal in deep geologically-stable rocks will be necessary. When full, disposal sites would have to be sealed so that they were safe, even if no records were to survive on their location and contents. No such sites yet exist.

Despite the cost of nuclear power plants, the time needed to build them and the problems of dealing with radioactive waste, it now seems likely that there will be a resurgence in their construction. If the increase in average global temperature is to be kept below 3°C by the end of this century (roughly coresponding to an atmospheric carbon dioxide concentration of 550 parts per million (see **Chapter 4.8**), electricity generation will have to move rapidly from fossil fuel to nuclear fission – unless carbon capture and storage can be deployed on a masive scale. But proposals for new nuclear power stations 'would need to be accompanied by acceptable plans for both short-term storage and long-term disposal of the waste that would be produced' (Royal Society Report on the Storage of Nuclear Waste, 2002).

8.3 *Nuclear energy from fusion*

Energy is also released when elements lighter than iron fuse together to make heavier elements, losing mass in the process. Of all the possible combinations of light elements, the reaction between the two isotopes of hydrogen, deuterium (^{2}H) and tritium (^{3}H) is the most favourable for energy generation, in that it takes place at the highest rate at the lowest temperature – although this temperature is of the order of 100 million °C.

$^{2}H + ^{3}H \rightarrow ^{5}He \rightarrow ^{4}He + n + \text{energy}$

At such temperatures the deuterium and tritium isotopes exists as plasma, an electrically-neutral gas in which electrons and protons are no longer associated together in atoms. Being positively charged, electrostatic forces cause the naked deuterium and tritium nuclei to repel each other strongly: only when brought very close together can the strong nuclear force (an attractive force that operates over very short distances) overcome the electrostatic repulsion and bring about fusion. These enormous temperatures are required to give the nuclei sufficient kinetic energy to come close enough for the strong nuclear force to operate.

Several ways are currently under investigation for bringing the deuterium and tritium nuclei together at temperatures high enough for them to fuse. One is the tokamak, a doughnut-shaped chamber in which the plasma is contained by magnetic fields. There are enormous technical problems in stabilizing the plasma in a tokamak for long enough to produce a useful release of thermonuclear energy. In addition, the walls of the tokamak must be capable of withstanding very high temperatures and intense neutron bombardment. An international consortium has come together to build a large-scale tokamak (to be called ITER) in France and it is hoped that this will, in turn, lead to a prototype reactor capable of generating electricity.

Hybrid reactors, in which a fusion core is surrounded by a fission reactor, have also been proposed. In such a reactor, the fission ‘blanket’ absorbs the high energy neutrons produced by the fusion core, thus reducing the neutron flux reaching the outer wall of the reactor. In turn, the fission energy produced in the blanket helps maintain the high temperature needed for fusion in the central plasma.

Another approach is to use inertial confinement. Powerful laser beams are focused on a fuel pellet containing the deuterium and tritium, exploding the outer layer of the pellet. The resulting recoil heats the pellet core and compresses it to a very high density. In one proposed design (to be called HIPER), lasers will first be used to heat and compress the fuel pellet, followed by a short pulse from another very high power laser to ignite the reaction. Very recently, the US National Ignition Facility has tested an assembly designed to focus laser energy onto a tiny gold hohlraum containing the deuterium/tritium mix. The X-rays produced when the laser beams strike the hohlraum compress the fuel to ignition point. Up to now, the energy needed to bring the deuterium and tritium together is greater than that generated from the reaction – and this holds for both tokamaks and inertial confinement. A fusion reactor has a potential advantage over a fission reactor in that it does not produce long-lived radioactive waste: furthermore a runaway reaction cannot occur, since the fuel only enters the reactor as needed. Deuterium is abundant: every litre of water contains 0.017 g deuterium, and tritium is easily made by neutron irradiation of lithium, which is also common. Fusion of light elements may ultimately be the method of choice for large-scale electricity generation, but current opinion is that many more years of expensive research and development will be needed before it becomes economic.

8.4 Hydroelectricity

Hydroelectricity, in which the potential energy of water falling from a height is used to drive a turbine connected to a generator, is by far the most widely used renewable energy source, producing 16 % of the world’s electricity in 2005 (**Figure 3.3**). Hydroelectric power is ultimately solar energy, the water evaporated by solar radiation falling as rain or snow on elevated land. Usually a dam across a river is used to produce a head of water sufficient to drive a turbine. In the developed countries most suitable rivers and dam sites have already been exploited, so there are few opportunities to increase hydroelectric generation. It is therefore not surprising that most of the large hydroelectric plants now in construction are in developing countries – for example the Three Gorges Scheme in China. Dams flood otherwise-usable land upstream, as well as causing environmental damage through trapping of river-born silt and restricting the movement of fish. Large quantities of methane can be evolved in the period immediately after flooding if the dammed water covers an uncleared forest or other large stock of undecomposed organic matter. On the positive side, dams can help control flooding downstream and ease navigation through difficult sections of river.

The power (P, in watts) generated by a hydroelectric power plant is given by
$P = h\alpha\rho gF$
where h is the head of water, in m, α is a machine efficiency factor, usually around 0.75, ρ is the density of water, in kg m^{-3}, g the acceleration due to gravity, in ms^{-2}, and F the flow of water, in m^3s^{-1}. The main cost of a hydroelectric power station is in its construction, with a long plant life (some now being more than 100 years old) and low running expenses. Hydroelectricity is a particularly valuable component of any electricity grid because it can respond to changes in demand very quickly, just by opening the flow of water to a turbine. Pumped hydroelectric power plants, in which the turbines pump water from a lower to a higher reservoir at times of low electricity demand, when there is spare generating capacity, and then use this water to generate electricity at times of peak demand, are currently the only way of storing electrical energy on a scale large enough for power-grid use.

8.5 Wind energy

The Sun does not heat the Earth uniformly – some places are warmer than others. This differential heating causes the winds – warm air is lighter than cold air and so rises, allowing colder denser air to rush in. Wind direction and speed are of course modified by height above the ground, topography, the Coriolis force (caused by the rotation of the Earth) and many local factors. Although windmills have been used for centuries to grind grain and pump water, it is only in recent decades they have been used to generate electricity on a large scale, with wind-driven generators accounting for 0.7% of the world's total electricity production in 2006. In January 2008 the total world installed capacity was 94 GW, with a use factor of about 20 %.

The power (P, in watts) from a windturbine is directly proportional to the area (A, in m^2) swept out by the blades and the cube of the wind speed (V, in ms^{-1}), the relationship being
$P = 0.5\ \alpha\rho A\ V^3$
where ρ is the density of air, in kg m^{-3} and α is a turbine efficiency factor that depend on the turbine design and is typically 0.3-0.4. When a windturbine takes energy from the wind, the air slows down and spreads out. This places a limit on the energy that can be extracted, a limit given by the Betz law. This law says that even the most efficient windmill cannot extract more than 59 % of the energy in the incoming wind.

Because power from a windturbine is proportional to the cube of wind speed, much of the energy comes in short bursts – in one case, half of the available energy arrived in just 15% of the operating time. At very high wind speeds, windturbines blades must be furled to prevent damage to the machine. Because of the intermittent nature of wind power, onshore wind turbines only operate for part of the time – the UK target is 30 % of the rated power output over a period of a year, but only a few wind-farms in Scotland are able to reach this target. Offshore winds are more dependable and most of the wind-farms now in construction in the UK are offshore, despite the extra costs in construction and maintenance, not to speak of the cost of bringing the electricity ashore. As wind speeds tend to increase with height, wind turbines on land are mostly sited on the tops of hills, often in areas of natural beauty and this can make them visually obtrusive. Wind turbines that are well offshore are usually more acceptable – but more expensive to build and maintain.

A typical modern windturbine has a diametre of 50-80 m, with three blades rotating at about 15 rpm, driving a gearbox which rotates the generator shaft at some 2000 rpm. The largest wind-driven generator now in operation has a potential output of 6 MW. However wind turbines cannot be scaled up indefinitely: although the power output is proportional to the square of the blade length, the mass of the whole structure is proportional to the cube of the blade length. For convenience in construction and maintenance, wind turbines are commonly mounted in groups, termed wind-farms, although individual turbines must be well spaced out, to avoid interfering with each other's air flow. Wind power is only predictable a day or so in advance, so that wind-generated electricity must either be stored (for example by a pumped hydroelectric system) or backed up by a source of electricity that does not depend on the weather, such as a gas-fired turbine. Most power grids are flexible enough to accept a substantial contribution by wind power without difficulty – but 20 % has been suggested as an upper limit.

8.6 Wave energy

Any country with an oceanic coast, particularly if exposed to the Westerlies that blow between 30-60^{o}N and 30-60^{o}S, has a potential source of energy in the waves. Such coastlines receive an average of 40-70 kWm^{-1}over the course of a year. Many different ways of harnessing this energy have been proposed (for drawings of six see Nature, 2007, **450**, 157) but, in contrast to wind turbines, no one has yet constructed a wave-driven generator that has delivered power on the MW scale to a grid over a run of years. Apart from the intermittent nature of wave energy, which it shares with wind energy, any system of harnessing wave energy has to contend with the occasional huge wave. Again and again, such exceptional waves have brought grief to otherwise-promising systems. Wave energy is dissipated in shallow water, so any system for utilizing wave energy in the open sea has to be located in deep water – but not too deep, otherwise there are problems in providing firm anchorage. Shore-based systems such as the oscillating water column, in which the waves beating on a deep-water shore compress and decompress an air chamber that drives a turbine, may prove easier to service and maintain. Whether or not wave energy can be consistently harnessed on anything but a small scale has yet to be shown – but then wave technology is years behind wind turbine technology.

8.7 Energy from direct solar radiation

The energy available from direct solar radiation is enormous compared to human energy demands: even in Spitsbergen, far north of the Arctic Circle, solar radiation provides 1.66 kilowatt hours per square metre per day, averaged over the whole year. Needless to say, none of this comes in November, December or January - see **Figure 8.1**. Dry sunny desert places like Mauritania receive most (for example 5.76 kWhm^{-2}d^{-1} in Nouakchott; **Figure 8.1**), whereas cloudy places near the equator such as Libreville in Gabon receive somewhat less (4.70 kWhm^{-2}d^{-1}, although this is spread more evenly throughout the year; see **Figure 8.1**). Direct solar radiation can be used in three main ways – by utilizing the heat produced when the radiation is absorbed, by using solar photons to release electrons from a semiconductor (the photovoltaic effect), or by using the photons to split water molecules into hydrogen and oxygen.

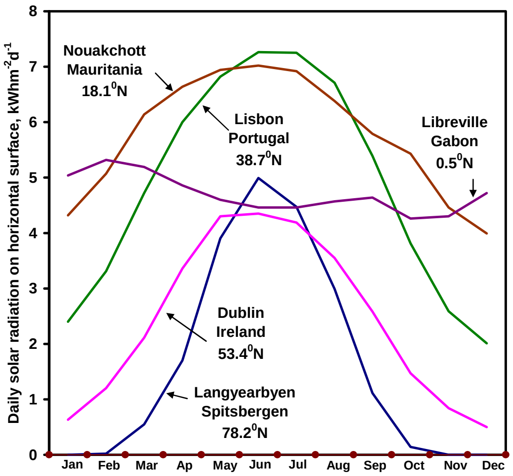

Figure 8.1 Solar energy received by locations near the western coasts of Europe and Africa.

From NASA Surface meteorology and Solar Energy: RETScreen data. The data plotted are for a pixel centred on the named town or city.

Solar panels are already widely used to produce hot water for domestic use. The panels must be located on roofs with a suitable inclination to the Sun and the system backed up for use at night by an insulated tank or by a supplementary electricity supply.

The problem is that sunlight is in shortest supply when most needed - at high latitudes in winter. On the other hand, air conditioning is most needed at low latitudes in summer and domestic systems that use solar heat to drive an air-conditioner via a low boiling-point refrigerant are being developed. Solar heating can also be used to generate electricity on the commercial scale – for example a recent development in Spain uses an array of mirrors to focus sunlight onto pipes containing a heat-transfer oil, which is then used to raise steam via a heat exchanger, the resulting steam being used to drive a turbo-generator. Working at peak capacity, the plant can generate 11 MW.

The photovoltaic effect, by which photons generate an electric current in semiconductors, is widely used, but as yet on a small scale – in 2007 only 0.23 % of the world's total electricity generating capacity was photovoltaic. It is, however, growing rapidly – in 2006 the annual growth rate was nearly 60 %, greater than any of the other major sources of renewable energy. A single photovoltaic cell (**Figure 8.2)** produces only half a volt or so and such cells are usually combined into an array. The energy generated can be used directly or, more usually, converted to alternating current at mains voltage by means of an inverter. Most of the cells now in use are based on silicon, even though such cells are expensive to make and not particularly efficient in converting sunlight to electrical energy - efficiencies of 10 % being typical for commercial silicon arrays. The solar energy not converted to electrical energy is lost as heat – and efficiency falls off as the cell heats up. As with all direct forms of solar power, photovoltaic systems need backup at night. They are potentially at their best in areas such as the Sahara, with little cloud and near-vertical insolation – in theory, a few percent of the Sahara could provide all of the world's electricity, even with cells that are no more efficient than those currently in production. The efficiency of photovoltaic cells falls off in cloudy conditions i.e. in diffuse light, but not so sharply as with focused systems for harnessing sunlight. Although at present electricity from photovoltaic cells is several times as expensive as from natural gas, photovoltaic cells, backed by battery storage, are already economic in remote sunny places where it would cost too much to connect to mains electricity. If cheap durable photovoltaic cells can be manufactured in quantity and if low-loss

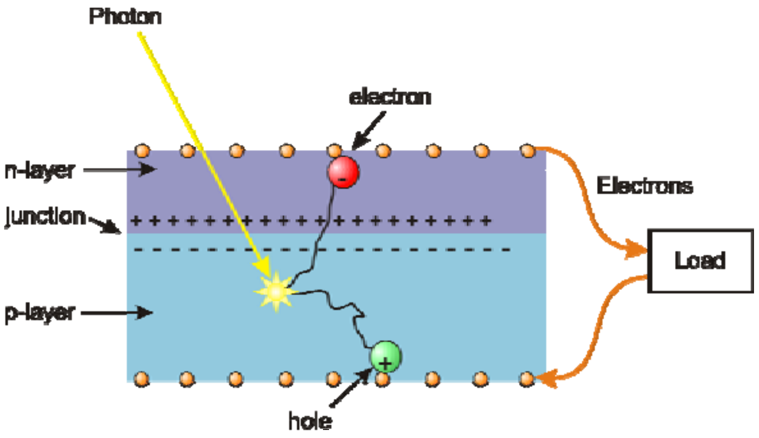

Figure 8.2 How a simple photovoltaic cell works.

From the top, the cell contains a conductor, a layer of silicon, a junction with another layer of silicon and at the bottom, another conductor. The silicon at the top side of the junction (the negative or n-layer) contains a small amount of an element such as boron (an electron acceptor) and the silicon on the bottom side of the junction (the positive or p-layer) contains a small amount of phosphorus (an electron donor), the net result being an electric field across the junction. When a photon of the right energy strikes a silicon atom, an electron is ejected, leaving a 'hole' (i.e. the absence of an electron). Under the influence of the electric field, the electron migrates to the upper conductor and the hole migrates to the lower conductor, producing a current that can do work.

ways can be developed for transmitting electricity (or hydrogen generated by electrolysis) over long distances, the world's hot deserts may become as desirable as oil fields.

Photovoltaic cells are already at least an order of magnitude more efficient in capturing solar energy than plants: a high-yielding crop of winter wheat grown at Rothamsted in central England fixed (in grain, straw and roots) only 0.7 % of the 3580 MJ m^{-2} of incident solar radiation received in a year. Plants grown especially for biofuel, such as the C-4 perennial grass *Miscanthus*, do better, but are still far less efficient than photovoltaic cells. In southern Illinois, *Miscanthus* fixed 1.1 % of the annual incident solar radiation (5640 MJm^{-2}) in the above-ground crop, harvested at senescence (Heaton et al. 2008. *Global Change Biology*, **14**, 2000-2014).

Various schemes have been proposed to locate mirrors above the Earth's atmosphere and focus the solar energy onto photovoltaic cells back on Earth. Another proposal is to locate a photovoltaic array in space and transmit the energy back via microwaves. Suitably located, such contraptions could return solar energy by day and by night – but are far beyond present technology.

8.8 Tidal energy

Gravitational forces from the Moon and Sun give rise to the tides, potentially one of the cheapest and most predictable sources of carbon-free electrical energy, once the initial costs have been met. The Moon generates two bulges in the level of the open ocean, each about half a metre in height, one on the side of the globe facing the Moon and the other on the side furthest away. The Sun generates similar but smaller bulges and, when Moon and Sun are in line, the bulges are at their largest - spring tides. Neap tides occur when the pull of Sun and Moon are at right angles to each other. As the Earth rotates under the bulges, any place in the open ocean will experience two high tides and two low tides every twenty-four hours and fifty minutes. When a tidal bulge reaches the coast (or, more accurately, when the coast approaches a tidal bulge), the bulge builds up, particularly in a shallow funnel-shaped estuary, where it can reach as much as 15 metres. Tidal streams or races are found where the flow is constricted, notably between islands or in the entrance to a large inlet. Although the tides can only generate electricty for part of the day, the times of high and low tide can be calculated many years into the future, so that the electricty output to a national grid from a tidal system can also be calculated in advance, unlike wind power, which cannot be predicted for more than a day or two ahead.

Electrical energy can be generated from the tides in two main ways, by placing turbines in a barrage built across a tidal inlet, or by placing the turbines directly in the tidal stream, thus making use of the kinetic energy of the moving water. The first method makes use of the difference in height between high and low tides (the tidal range) to drive turbines and generate electricity. The average power output from a barrage is roughly proportional to the square of the tidal range and the energy output is approximately proportional to the area enclosed by the barrage, so that a site with a large tidal range and a big enclosed area is best for tidal power generation. Such sites are not common. The biggest electricity generating plant worked by tidal energy is at La Rance, in France, where a barrage 330 metres long was build in front of a 22 square kilometre basin, with an average tidal range of 8 metres. In 2006 this plant celebrated 40 years of active service, during which time 20 billion kWh of electricity were generated without major incident or mechanical breakdown. Tidal barrage power schemes are expensive to build but have a very low running cost. The proposed Severn barrage would cost £15 billion to build, with an output of 8 GW, an estimated lifetime of 120 years and could produce 6 % of the UK electricity demand.

Tidal stream systems make use of the kinetic energy in currents to drive turbines, just as windmills use moving air. The turbines are anchored to the sea floor, with the blades positioned in the current flow above. The power output (P) is given by
$P = 0.5\ \alpha\rho A\ V^3$
where α is a turbine efficiency factor, ρ is the density of sea water, in kg m^{-3}, A is the area swept out by the blades, in m^2 and V is the flow velocity, in ms^{-1}. This expression is formally similar to that for a wind turbine (**Chapter 8.5**), but since sea water has a density of 1025 kg m^{-3}, compared to about 1.2 kg m^{-3} for air at sea level, the same power output can be obtained for a given flow rate with much shorter blades. Because power output is proportional to the cube of the stream velocity, turbines are best sited in fast tidal flows - but fast flows are not common and are often found in remote places, far from where the electricity is needed.

8.9 Geothermal energy

There is a net flow of roughly 40 TW (or 0.08 $Wm^{-2)}$ from the interior of the Earth to the surface and for decades a tiny part of this (geothermal) energy has been used for domestic heating and to generate electricity in geologically-suitable parts of the world. In 2006, 26 % of Iceland's electricity was geothermal: in New Zealand, about 7 %. At present, geothermal energy comes from steam generated by hot rocks near the surface, but in the future it may be possible to obtain geothermal energy almost anywhere by injecting water deep into the Earth's crust – although deep drilling is extremely expensive. Geothermal energy has the great advantage that the supply is continuous, day and night, thus providing baseline power. Once the drilling has been done and the necessary plant installed, geothermal electricity is cheap and virtually no carbon dioxide is produced.

8.10 Other ways of generating electricity

Wherever there is a difference in temperature between different parts of a system, there is an opportunity to extract useful energy. Tropical surface oceanic water can have a temperature of over 25 ^{o}C, yet this warm water can overlie deep oceanic water at 3-4 ^{o}C. This difference can, in theory, be used to drive a heat engine capable of generating electricity, a process called Ocean Thermal Energy Conversion (OTEC). The warm water is first used in an evaporator to vapourise the operating fluid (for example, liquid ammonia) in the heat engine. This vapour then drives a turbine. Cold water pumped up from the depths is used to condense the vapour, the liquid being returned by pump to the evaporator, just as in the Rankine cycle (**Figure 5.3**). Because the temperature difference is relatively small, the maximum efficiency of such a device is only 6-7 %, making energy extraction difficult and expensive. However the oceans are so vast that such low efficiencies might well be tolerated. As yet, OTEC has only been used experimentally on a small scale.

In the future, differences in salinity between sea water and fresh river water may be used to generate electricity. The energy ultimately comes from the Sun, which evaporates water from the saline oceans, water that returns to the sea in rivers. When fresh water from a river is separated from saline sea water by a semi-permeable membrane (i.e. a membrane that is permeable to water but not salt), the fresh water moves across the membrane into the saline water, diluting it and, in a closed system, setting up a pressure difference across the membrane. This pressure difference can be used to drive an electricity generator. The difference in salinity between fresh water and sea water can also, in theory, be used to drive a reverse electrodialysis power cell, a device that separates the sodium ions, which move to the cathode, from the chloride ions, which move to the anode, generating an electric current.

8.11 Electricity from renewable resources: an overall assessment

Of the various renewable resources (**Table 8.2**), solar energy is the one with most potential for generating electricity, by more than two orders of magnitude. Wave, wind, hydro and tidal generation come far below, in that order. Hydroelectricity is unique in that present capacity is roughly a third of potential capacity: with all the others, present use is only a tiny fraction of the potentially usable. Electricity from biomass is particularly uncertain, being based on estimates of the area of land across the world that could be used for growing biomass crops - but without affecting food production.

Photovoltaic power, solar heating, wind power, wave power and biomass all suffer from the same disadvantage: the power produced is small per unit area, so that extensive areas (or, for wave power, shore lines) are required for a significant output. Even the best of them, photovoltaic power, would require 40 sq km to generate the same quantity of electricity (~7x10^9 kWh) in a year as the 1000 MW coal-fired plant described in **Chapter 5.6**, assuming that the cells were located in a desert with an annual mean solar radiation of 5.76 kWhm^{-2}day^{-1} over the whole year, day and night (the figure for Nouakchott in Mauritania, see **Figure 8.1**), that the cells covered 90 % of the horizontal surface, that they had an efficiency of 10 % and that the whole system had a load factor of 90 %.

Table 8.2 Renewable sources of energy for electricity generation: installed capacity, and potential size of resource

Renewable resource	World installed capacity[a]	Installed capacity as % total world electricity generating capacity[b]	Potential size of resource[c]
	GW	%	TW
Hydro	**800**	**20.7**	**>10[d]**
Wind	**94**	**2.4**	**70[e]**
Tide	**0.26**	**0.007**	**3[f]**
Wave	**0**	**0**	**>100[g]**
Solar photovoltaic	**9**	**0.23**	**30000[h]**
Geothermal	**10**	**0.26**	**15[i]**
Biomass	**40**	**1.0**	**2.5[j]**

[a] From Schiermeier et al. 2008 Nature 454, 816-823. See also Chapter 4 in IPCC III 2007

[b] Taking world installed capacity as 3.87 TW in 2005, from EIA International Energy Outlook 2008

[c] This column gives potential size of resource, not electricity produced. Thus wind turbines usually generate only 20-30 % of their rated capacity and 2.5 TW of biomass would produce about 1 TW of electricity

[d] If all the world's rivers were turbined down to sea level - but only about 2.5 is realistically available - see[a]

[e] For suitable sites on *land* with windspeeds of >6.9 ms-1 at 80 m height - see[a]

[f] Of which some 1 TW is in shallow water - and only part of this is realistically available - see[a]

[g] Of which the accessible global resources make up only 1-10 TW - see[a]

[h] Incoming solar radiation over *land*, less that reflected by clouds or absorbed by the atmosphere

[i] Over *land,* but unlikely to reach a TW with present technology[a]

[j] Assuming 0.5 billion ha of land suitable for rain-fed biomass production and not in agricultural use, a yield of 10 t dry biomass ha^{-1}yr^{-1} and 16 GJ per tonne dry biomass

One great advantage of generating electricity from coal, gas or nuclear fission is that the output comes from sites that are relatively compact – and these sites can be placed near where the electricity is needed. The best sites for wind, tide, wave and solar photovoltaic power are often far from where the electricity is wanted, so that long power lines have to be constructed, with their attendant losses. Over long distances, these losses are greater with alternating current than with direct current, making DC transmission, which is technically more complex than AC transmission, cheaper for distances of more than about 800 kilometres.

An electricity grid must have back-up from nuclear, hydro, coal or gas fired generators if there is no wind, the tide is on the turn, the sea is calm or it is dark. At present there is no large-scale way of storing electricity except by pumped hydro – but suitable sites for this are rare. If renewable energy is to make up more than 20 % or so of grid power, new ways of storing energy will have to be developed. Super DC electricity grids, connecting remote sources of renewable energy, might also allow this limit to be exceeded – for example by combining wind power during a stormy Northern night with photovoltaic power from a sunny Saharan site during the day.

Energy can be stored in batteries, or as compressed air, or in super capacitors and it may be possible to scale up one or all of these. Flow batteries, which store energy in their electrolyte, rather in the electrodes, as in conventional batteries, are relatively easy to scale up, because the electrolytes can be held in tanks outside the actual battery. Much of the energy needed to operate a gas-fired turbine is spent compressing air before it is mixed with the gas and burned. If stored compressed air is available from a renewable source, the turbine will generate more electricity for a given release of carbon dioxide. Inertial storage in flywheels has also been suggested, as has the manufacture of hydrogen when there is a surplus of electricity, with the hydrogen then used to fuel turbines at times of shortage – see **Chapter 8.12**.

8.12 The hydrogen economy

One possible way to break the link between the human demand for energy and fossil fuel is to move to a hydrogen economy. Hydrogen has a high heat of combustion (**Chapter 3.2**) and the product of combustion is water, so it has an immediate attraction as a clean energy source. Hydrogen can be used as fuel in internal combustion engines, to fire gas turbines and to generate electricity in fuel cells.

In a fuel cell, hydrogen is supplied to the anode, where the hydrogen is catalytically dissociated into protons and electrons. The protons move through a membrane (or in some types of cell, an electrolyte such as phosphoric acid) to the cathode, where they react with oxygen from the air to form water (**Figure 8.3**). This membrane is only permeable to protons, so that the electrons must return via an external circuit, generating an electric current as they go. A serious problem with the present generation of fuel cells is that they require expensive catalysts, notably platinum, for efficient operation.

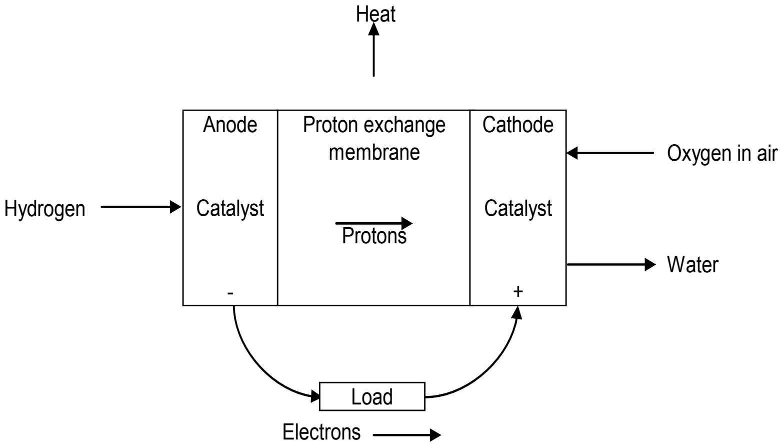

Figure 8.3 How one type of fuel cell works.

The hydrogen gas is catalytically ionized at the anode to electrons and protons, which travel by separate paths to the cathode, where they react with oxygen to form water.

At present, most of the hydrogen manufactured comes from steam reforming of natural gas at high temperatures:

$CH_4 + H_2O \rightarrow CO + 3H_2$

More hydrogen is then generated by the water-shift reaction:

$CO + H_2O \rightarrow CO_2 + H_2$

A hydrogen economy based on natural gas has therefore no net effect in reducing carbon dioxide production: it merely moves the production of carbon dioxide from the place of use (for example as a vehicle fuel) to the place of manufacture. Hydrogen can only be regarded as a ‘clean’ fuel if CCS is used to trap and sequester this methane-derived carbon dioxide. However hydrogen can also be produced on a large scale by electrolysis of water to give hydrogen and oxygen, although this is extremely energy intensive, roughly 50 kWh being required to produce 1 kg of hydrogen gas. If the electricity required for electrolysis comes from non-fossil sources (hydroelectric, nuclear, solar, etc.) the link between hydrogen manufacture and fossil fuel is broken.

Plants use sunlight to split water into oxygen and hydrogen, which is then used to reduce carbon dioxide to carbohydrates (**Chapter 2.4**). By analogy, inorganic catalysts that use sunlight to split water to oxygen and hydrogen are under investigation - some recent work with the semiconductor titanium disilicide achieved 4 % conversion efficiency in the laboratory. Perhaps this will lead to new power sources in sunny parts of the Earth, in competition with photovoltaic cells.

In a hydrogen economy, hydrogen could be used both as an energy carrier and an energy store. However it is a poor carrier: a liter of of gasoline contains 116 grams of hydrogen, but a liter of liquid hydrogen only 71 grams. Because of its low density, hydrogen is difficult to store, either in liquid or gaseous form. Compresion of the gas requires energy and storage tanks capable of withstanding high presures. Energy is required to make liquid hydrogen and the liquid, which boils at 20 ^{o}K, is not easy to keep. Better ways of storing hydrogen, possibly by chemical or physical absorption, will need to be developed if the hydrogen economy is to be widely used.

Hydrogen is produced by a number of microbial processes – for example, organisms that normally fix nitrogen from the air will generate hydrogen if deprived of nitrogen. Similarly, some photosynthetic microorganisms can produce hydrogen in the absence of carbon dioxide. It may be that such processes can be scaled up – but much research is needed to see if the production of hydrogen by microbes is viable on a commercial scale.

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Chapter 9 – adapting to climate change

9.1 Population growth

Some degree of adaptation to climate change is inevitable, no matter what is done in the future to restrict the use of fossil fuels. One way is to discourage population growth. As populations increase, so does the demand for energy, food, water, land, metals, building material and a multitude of other needs. The growth of the human population, from one billion in 1800, to six billion at the end of the twentieth century, has followed an amazingly smooth trajectory, despite wars, pandemics and famines (**Figure 3.6**). Although the annual rate of increase in population is now slowing, from a maximum of 2.2% in 1963 to the present 1.19 %, the population will continue to rise for many years, the current projection for 2050 being 9.1 billion (UN medium scenario, 2008 revison, assuming no major disasters).

No one really knows how to control population growth – the humane ways are said to be education, particularly of girls, better living standards and freely-available contraception. Legislation – for example the single child policy in China - can be effective, but harsh on those directly affected. In some prosperous countries, for example Germany and Japan, populations are now in spontaneous decline but in others, such as the UK and the USA, growth continues, mainly as a result of immigration by people from poorer countries looking for work. It is no coincidence that the largest birthrates per woman are in the poorest countries, stricken by war, political corruption, unemployment and lack of food, where infant mortality is at its greatest. The prerequisites for a fall in the birth rate seem to be peace, good governance and rising prosperity.

Human diseases and pests once confined to the tropics could well move into new areas – for example malaria is spread by *Anopheles* mosquitoes, which require moist heat to flourish. Diseases such as malaria can be controlled by modern public health measures and by medical technology - but at an economic cost. Fewer people may well die of cold – but more in heat waves, although measures such as air conditioning can be taken to protect the vulnerable, again at a cost.

If certain parts of the world become hotter, drier and less able to carry their present populations, others, particularly in high latitudes, may well become more attractive to human settlement. Pressure will build up for massive population movements – with all the associated ethnic, political, legal and economic problems. Mass population movement is nothing new - Ireland lost half its population in the decades following the famine, with more than 4.5 million people leaving between 1850 and 1913 to live overseas, many to the then-open lands of the USA, Canada and Australia.

9.2 Adapting to climate change – sea level increase

A rise in mean sea level is all but inevitable because of climate changes already under way – see **Chapter 4.5**. If the predicted rise of 1.4 m by 2100 (**Chapter 4.5**) materializes, coastal defenses will have to be constructed (or improved) in many parts of the world. A UN report (UN FPA State of World Population 2007) states that only 2 % of the world's land area is classified as Low Elevation Coastal Zone - but 10 % of humanity live in that zone. Effective coastal defenses are very expensive in money and energy, but the Dutch experience shows that a prosperous economy can be built behind sea defenses, remembering that these defenses are not the work of a single generation, but were built up over the centuries. The deltas of the Nile, Ganges, Brahmaputra, Irrawaddy and Mekong rivers are low lying and densely populated, mostly by poor people. Even a modest rise in sea level would mean disaster for these communities (Dasgupta et al. 2007. World Bank Policy Research Working Paper. No. 4136).

There are two strategies to meet rising sea levels: *retreat*, by moving to higher ground; *defend*, by building new sea defenses and raising old ones. Which strategy will be followed in a particular place will depend on the money available to build defenses, the value of the location to be abandoned and the speed at which the sea rises.

9.3 Adapting to climate change – water resources

Although it is likely that warming will cause an overall increase in global precipitation, most of the Atmospheric-Ocean General Circulation Models considered by the IPCC (**Figure 4.3**) predict that precipitation will decline in the semi-arid zones that lie on either side of the wet equatorial belt. Unfortunately, many parts of these semi-arid areas are already densely populated - and population growth is particularly rapid in several of the countries that lie in this zone. Increasing living standards and growing populations increase the demand for water and if this rise occurs in the semi-arid zone, water shortages, already present, will increase in severity, quite apart from any additional contribution from climate change.

By far the biggest user of water is agriculture, which currently takes about 70 % of global freshwater water resources (World Resources Institute, 2006). Adaptation to water shortage, by using less wasteful irrigation techniques, better storage of seasonal rain, more efficient recycling, etc., will help, but most authorities (see, for example, UN Water Development Report 2, 2006) agree that water will become an increasingly crucial issue for people living in mid-latitudes in the twenty-first century.

Transport of water, for example by long-distance pipes, is an option – if a surplus is available within a feasible distance. Desalination of sea water is another option, if very demanding in energy – one of the most energy-efficient plants now operating in the world (the Tuas installation in Singapore) requires 4.1 kWh per cubic metre of desalinized water. The Tuas plant uses reverse osmosis, a process in which sea water is forced under pressure through a semi-permeable membrane that water molecules can pass through but salt cannot, the salt being separated as a concentrate. Vacuum distillation in its most efficient form, multi-stage flash distillation, requires even more energy than reverse osmosis. Brackish water, where available, of course requires less energy for desalination than sea water.

9.4 Adapting to climate change – food security

Rising populations require more food at a time when climate change is beginning to have an impact on agricultural productivity in certain critical parts of the world. The fundamental limit on agriculture is the amount of land available. About 37 % of the Earth's land surface (excluding Greenland and Antarctica) is now used for agriculture, used in its widest sense to include cultivated land, managed grassland and permanent crops (see **Figure 9.1)**. The area used for agriculture, now around 50 M km^2, has increased with the growth in human population, with about 5 M km^2 added over the last forty years.

Although the area of agricultural land per person has decreased, increases in agricultural productivity per unit area of agricultural land have allowed food supply per person to increase, in both developed and developing countries (see IPCC, 2007: *Climate Change*.III, Chapter 8). Even though it is virtually certain that more land will be cleared for agriculture in the future, notably in South America and Sub-Saharan Africa, productivity per unit area of agricultural land must continue to increase if growing populations (see **Figure 3.6**) are to be adequately fed. Ominously, world grain yields increased by only 1.2 % per hectare per year between 1990 and 2007, a rate of increase roughly half that (2.1 %) between 1950 and 1990 (Brown. L.R. 2008. *Plan B.3.0. Mobilizing to Save Civilization,* Norton).

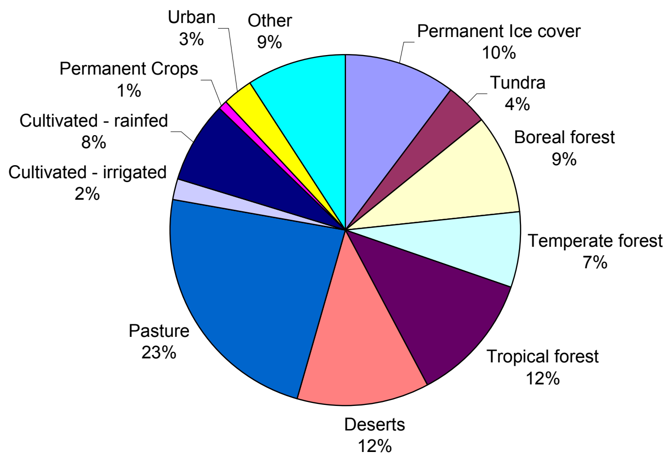

Figure 9.1. Global land use.

Agricultural data from FAO Statistics Global Outlook 2006: other data from IPCC, 2007: *Climate Change*. II, Chapter 4. Some marginal desert areas may also be included in the ‘pasture’ sector. This double counting may then make the ‘other’ sector, which includes bare rock, mountain peaks, etc., too small. Total land area of the world is 149 Mkm^2. About 6 % of the world’s soils are salt-affected.

Agriculture has been practiced for millennia in many parts of the world, often with yields that have increased over the years. All successful long-term agricultural systems have one thing in common – the nutrients removed in the produce are replaced, either by efficient recycling, (traditional Chinese rice culture), by annual additions of silt (the Nile), by fresh falls of volcanic ash, or by regular applications of fertilizer (modern commercial farming). However there are also places where production is declining – see the United Nations Environment Programme Global Assessment of Human-induced Soil Degradation (UNEP GLASOD) maps. Land has been ploughed in places that are far too dry for permanent arable cropping, for example the Eyre Peninsula in Australia or the Virgin Lands project in Kazakhstan. Forests have been cleared for crops on land so steep that serious – and often irreversible - erosion has occurred. Likewise, overgrazing by domestic animals has exposed pasture land to erosion by wind and water in many parts of the world, particularly in arid and semi-arid regions. But with knowledge and money, erosion can be controlled – except in the most unfavourable topography.

Agriculture in many parts of Australia, the South-West USA, North China and Northern India depends on irrigation from subterranean aquifers containing fossil water and will come to an end (at least in its present form) as these aquifers are exhausted - unless other cheap sources of water can be found. Because these aquifer-fed areas lie in the semi-arid zones, this loss of productive land could well be exacerbated by changes in rainfall caused by global warming.

Salts, notably sodium chloride, often accumulate in irrigated soils, rendering them infertile: about 0.1 % of the world’s agricultural soils are lost to salinization every year. Although these salts can often be leached out of the rooting zone, this requires copious quantities of water in areas where water is scarce, as well as extensive drainage systems to carry off the salty drainage water. Land suitable for permanent agriculture must be cherished, farming systems that permanently damage land avoided and land presently unsuitable for agriculture left alone – at least until we learn how to use it.

Some of the changes to agriculture brought about by global warming could be beneficial, for example if cereal cultivation moves northwards in Canada and Russia. Others could be detrimental, if, as is thought likely, Southern Europe becomes warmer and drier. For the three cereals wheat, maize and barley, there is a negative yield response to increased temperature, a response that cannot be explained by changes in precipitation (Lobell & Field. 2007. Environ.Res. Letters, doi:10.1088/1748-9326/2/1/014002). To some extent, crops and cropping patterns can adapt to these changes. Plant breeders may be able to develop crops that can use less water, tolerate higher temperatures, or survive increasing salinity.

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Chapter 10 - economic incentives to reduce emissions

10.1 Costs and benefits

In the end, decisions about how to control the release of greenhouse gases to the atmosphere have to be based on ethics - what weight should we give to the interests of people as yet unborn? Finite resources such as cheap pumpable oil will be almost certainly be exhausted in a generation or two - yet a renewable resource like prime agricultural land can produce food indefinitely if properly cared for. Marx (Groucho, not Karl) once asked 'what has the future done for me' and if we put no value on those not yet born, there is no point in spending money on them, which is an ethical conclusion not many people would accept.

If we do accept that we have an ethical responsibility to future generations, we then have to consider how best to spend money on controlling the release of greenhouse gases to the atmosphere. This is difficult because neither the costs – to be paid now and in the foreseeable future, nor the benefits, to be received in the remote future by future generations - can be accurately quantified. Economists use a factor called the 'discount rate' to calculate the present cost of future benefits. (For a discussion of this term as applied to long-term climate change see IPCC, 2007: *Climate Change*. III, Chapter 2.4.2.1). If the discount rate is set low, it is well worth spending money now to avoid great expense in the future. If it is set high, less money need be set aside now to avoid the same future expense. This can be illustrated by a simple calculation that ignores inflation and is based on the compound interest formula. With a discount rate of 1%, a sum of 37p would have to be invested *now* to mend £1's worth of damage from climate change in 100 years time: with a 4% discount rate, only 2p would have to be invested *now* to mend the same amount of damage. The choice of the best discount rate (or range of rates) to alleviate the future costs of global warming is a highly technical issue, hotly debated by economists. Amongst many other factors, the choice of discount rate depends on how much money is spent on technological advance to control greenhouse emissions, when it is spent, how it is spent - and with what success: none of these can be known in advance.

According to the Stern Review (for reference, see end of Chapter) 'mitigation - taking strong action to reduce emissions – must be viewed as an investment, a cost incurred now and in the coming few decades to avoid the risks of very severe consequences in the future. If these investments are made wisely, the costs will be manageable, and there will be a wide range of opportunities for growth and development along the way'. The Stern Review uses a discount rate of around one percent, and other economists have sharply criticized Stern for using such a low discount rate. Thus Nordhaus (for reference, see end of Chapter) pointed out that the drastic measures proposed by Stern become much less attractive from the economic point of view if a 4 % discount rate is used. Nordhaus calculated that by far the most efficacious policy over the period 2005-2105 would be to actively promote strategies that avoid fossil fuels, such as low-cost solar energy, geothermal energy, etc., the second best being a global carbon tax that increases with time.

Leaving arguments about the choice of discount rate to professional economists, I shall merely outline some of the economic tools that have been proposed to reduce the quantity of greenhouse gases emitted by human activities.

10.2 Economic tools for reducing the release of greenhouse gases

A direct carbon tax, at so much per tonne of fossil carbon dioxide emitted to the atmosphere (or its equivalent in the other greenhouse gases produced by human activities), applied world-wide, is simplest, potentially the most effective, but almost certainly too difficult to achieve politically. Of the more realistic policies, carbon credits are currently the most important – although the failure of the 2009 Copenhagen Conference to come up with anything more than a statement of intent to limit the global rise in temperature to 2°C does not argue well for the future of such credits. A Carbon Credit, which can be bought or sold on the open market, gives the owner the right to emit one tonne of carbon dioxide, or its equivalent in other greenhouse gases. Cap-and-trade (sometimes called emission trading) is a term used for the process by which the overall number of carbon credits to be bought and sold is set for a particular country – or for a group of industries within that country. Once set, the carbon credits are bought and sold between emitters as necessary. Thus a company will buy credits if it finds itself over its cap for a particular year, or sell them if it has credits to spare. Because the number of credits issued is designed to decrease, year by year, these credits will appreciate in value, so that the pressure to reduce emissions will increase. A particular advantage of cap-and-trade is that emissions are controlled in the most economic way: a company that can reduce emissions cheaply will then sell its unused credits to one that cannot.

The United Nations Framework Convention on Climate Change (UNFCCC) took place in 1992 and called for global action 'to protect the climate system for present and future generations'. The resulting treaty has now been signed by virtually every country in the world. This treaty did not set manditory limits on greenhouse emissions, but it included provisions to set up future meetings to agree on specific targets. The most important of these meetings was held in Kyoto in 1997 and lead to the Kyoto Protocol, which came into force in 2005, although certain industrialised countries have yet to ratify it. The major distinction between the Kyoto Protocol and the Convention is that while the Convention *encouraged* industrialised countries to reduce greenhouse gas emissions, the Protocol *commits* them to do so. The Kyoto Protocol calls on Annex 1 Parties (a term that includes most of the industrialized countries but excludes developing countries, which are termed Non-Annex 1 Parties) to meet their targets through the operation of three market-based mechanisms: Emission Trading, the Clean Development Mechanism and Joint Implementation. – for details, see UNFCCC. 2007. *Uniting on Climate. A guide to the climate change convention and the Kyoto Protocol*.

Emission Trading or 'cap and trade' has been damaged by over-generous issue of credits and by claims for credits from operations that contribute little to the reduction of greenhouse gases. Busineses are said to have been paid for making reductions in emissions that they would have made anyway. Another problem is that industries that cannot meet their emission limits will merely move their operations overseas, to places where there are as yet no limits. Nevertheless, emission trading remains the most ambitious and realistic of the economic tools for controlling emisions. Just as in the economic crash of the early 1930s, the current economic crisis will no doubt cause emissions to fall for a time, a fall already reflected in the declining price of carbon credits. If credits decline in value, the incentative to replace fossil fuels with non-polluting sources of energy will also becone less.

The Clean Development Mechanism allows developed countries (Annex 1 Parties) to meet greenhouse gas reduction targets by paying developing countries (Non-Annex 1 Parties) to cut emissions or promote policies such as reforestation. The carbon credits thus earned go to the Annex 1 country. Thus a company in one developing country was paid to trap HFC-23 (trifluoromethane), a greenhouse gas 12000 times more potent than carbon dioxide. HFC-23 is formed during the manufacture of the refrigerant HCFC-22 (for which see **Table 2.3**) as an unwanted by-product, previously vented to the atmosphere. The trapping of HFC-23 is clearly a good thing, but the question remains – should a plant incapable of trapping such a dangerous greenhouse gas ever have been built?

Joint Implementation is a complex process by which a developed country ***A***, in Annex 1, can invest in emission reduction projects in a less-developed country ***B***, also in Annex 1, where it is cheaper to reduce emissions. For example, a inefficient coal-fired power plant in country ***B*** might be replaced by a more efficient gas-fired power plant, so that by investing abroad, rather than at home, country ***A*** can lower the cost of complying with its Kyoto target. Joint Implementation offers country ***A*** a cost-efficient way of fulfilling part of its Kyoto commitment, with the host country ***B*** benefiting from foreign investment and technology transfer.

Subsidies, used wisely, are a powerful economic tool for encouraging a move away from fossil fuel. Inded it is difficult to see how something as complex and expensive as large-scale Carbon Capture and Storage (CCS) can be developed, tested and brought into commercial use, without financial help from government, i.e. a subsidy. Similarly, generous subsidies will be needed for the disposal and safe storage of highly radioactive waste if electricity generation by nuclear fission is to make a comeback. On the other hand, ill-placed subsidies can distort markets: it has been argued that the US subsidy for producing bioethanol from corn increased food prices, with little if any gain from the reduced use of fossil carbon. It is often forgotten that fossil fuel is already heavily subsidised: in 2005 the International Energy Agency estimated that the world energy subsidy amounted to US$ 250 billion, of which oil alone received $90 billion. This subsidy not only protects the *status quo*, but is also a disincentive to innovation, because it makes it more difficult for innovators to compete with existing systems.

It is sometimes argued that rising energy prices will wean the world from fossil energy as the cheaper sorts of fossil fuel are exhausted. But it will be decades before oil and gas reserves run out - and coal reserves will last even longer (**Table 3.2**). Meanwhile carbon dioxide will steadily accumulate (**Figure 3.5**). Of course economic pressure operating through shortage could eventually make oil and gas less attractive than other sources of energy that are presently more expensive, for example nuclear fission or renewables, but it could also make it worthwhile to exploit fossil fuels like low-grade coal or oil from oil shales, which produce even more carbon dioxide per unit energy than present fuels.

Another argument sometimes deployed – although rarely explicitly - is that technological advance is likely to solve the problems we face from the widespread use of fossil fuels, so that there is no point in setting up complex economic instruments such as emission trading - new technologies will rapidly render them superfluous. Perhaps (say) nuclear fusion will provide all the cheap clean energy we need within a few decades, but then perhaps not. A great deal of damage could well be done if the unrestricted use of fossil fuels is allowed to continue until the new technologies are in place, whenever that might be. But even if technological change *on its own* is sufficient to end our dependence on fossil fuels, without recourse to economic measures such as energy trading, it still makes sense to spend money *now* to explore, research and develop the new technologies. Indeed, countries actively researching, developing and introducing such technologies may well put themselves at a competitive advantage over countries that do not.

In 2009 the McKinsey Company published a ‘Global Greenhouse Gas Abatement Cost Curve’ that gives a quantitative basis for deciding which of almost forty different actions could be most effective (and how much each would cost) in delivering greenhouse gas reductions (Pathways to a Low Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Co, 2009). For example, a move to nuclear electricity generation could reduce greenhouse gas emissions in 2030 by about 2.0 Gt CO_2e per year, but at an abatement cost of 10 euros per tonne CO_2e *above* ‘business as usual’, whereas measures to improve waste recycling could save about 0.8 Gt CO_2e per year, but at an abatement cost *below* ‘business as usual’of 12 euros per tonne CO_2e – i.e. a potential saving.

10.3 The Kaya Identity

The Kaya identity provides a most useful way of linking the social and economic pathways for the reduction of carbon dioxide emissions. According to Kaya, there are four ways of reducing emissions:
1. By reducing population
2. By reducing wealth
3. By reducing the energy required to produce one unit of GDP
4. By reducing the quantity of carbon needed to produce one unit of energy.
This is summarised in the Kaya identity,
$F = P*(G/P)*(E/G)*(F/E)$
$= P*g*e*f$
where F is the global emission of CO_2 from human activity, P is the global population, G is world gross domestic product (GDP) and E is global primary energy consumption. In the second form of the identity (below the first), *g* is global GDP per person, *e* is global primary energy consumption, divided by global GDP and *f* is global emission of CO_2 from human activity, divided by global primary energy consumption.

Elimination of people (P) on a scale sufficient to have much of an effect is politically and ethically unacceptable by civilized society. To call for an *overall* reduction of wealth per person (*g*) would be political suicide – although political errors could well allow it to happen - which leaves only the last two, *e* and *f*. The quantity of energy required to produce one unit of GDP (*e*) has been falling slowly over the last two decades in most countries, partly because of increasing production efficiencies and partly because service industries become more important as wealth increases. There is scope for *e* to fall much further. Likewise *f* is also slowly falling in most countries, with scope for large falls if fossil fuels are replaced by renewables and/or nuclear energy. Yet F can still increase if declines in *e* and *f* are outweighed by increases in both P and *g*, as has happened in the USA over the last two decades.

Another related term is carbon intensity, defined as F/G. Again, declines in carbon intensity (i.e. decarbonisation) can be outweighed by increases in P and *g*: thus carbon intensity dropped by 29% between 1990 and 2008 in the USA, although emissions increased by 16% over the same period.

Note that the terms in the Kaya identity are global. Strictly this identity should only be applied to a single country if imports to and exports from that country are taken into account when calculating *e* and *f*.

Decarbonization has proceeded at very different rates in different parts of the world (**Figure 10.1**). In Japan it has hardly changed since 1990, but has declined steadily (admittedly from a much higher level) in the USA. In China the pace of industrialization has increased greatly during the present decade and this is reflected in the recent *increase* in carbon intensity.

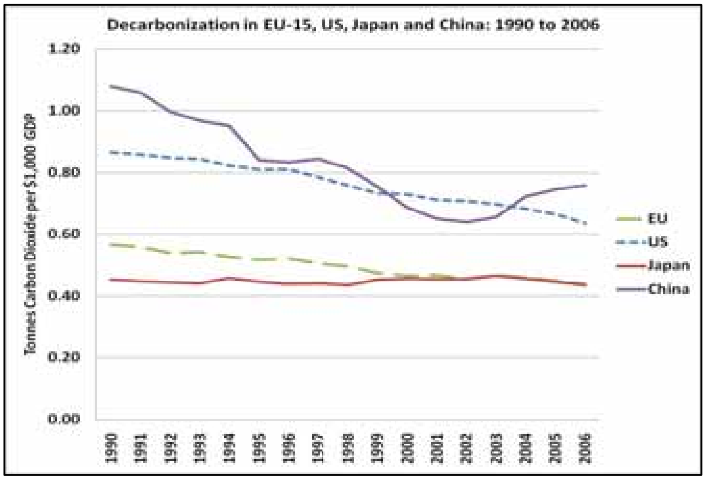

Figure 10.1. Decarbonization over the period 1990-2006 in China, USA, the European Union and Japan.

From Prins et al. 2009: ‘How to get climate policy back on course’, Institute for Science, Innovation and Society. Oxford. 6 July 2009, (their Figure 1). GDP is expressed as purchasing-power-parity adjusted 1990 Gheary-Khamis dollars.

Further reading for Chapter 10

Flannery, T. 2005. *The Weather Makers. The History and Future Impact of Climate Change*. The Text Publishing Co., Australia.
A passionately-argued book on the ethics of discounting the future.

IPCC, 2007: *Climate Change*. III, particularly Chapter 11.

Lomborg, B. 2007: *Cool It: The Skeptical Environmentalist's Guide to Global Warming*. Cyan/Marshall Cavendish, UK.
Accepts the likelihood of global warming, but highly critical of some of the more drastic cures that have been proposed.

Nordhaus, W.D. 2008: *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press. USA.
A detailed assessment of risks and curative actions.

Prins, G and eleven others. *How to get climate policy back on course.* Institute for Science, Innovation and Society, Oxford. 6 July 2009.
A trenchant criticism of Kyoto-based targets as a way of reducing emissions. Instead, the document advocates a policy that makes clean energy cheaper than ‘dirty’ energy at the point of use by the consumer, by subsidizing more efficient and less carbon-intensive production.

Stern, N. 2007. *The Economics of Climate Change*. Cambridge University Press, Cambridge, UK.
A grim forecast from the UK point of view, calling for immediate and stern action.

Stern, N. 2009. *A Blueprint for a Safer Future: how to Manage Climate Change and Create a New Era of Progress and Prosperity*. Bodley Head, UK.

Chapter 11 - Conclusions

Jonathan Swift once observed ‘How is it possible to expect that Mankind will take Advice, when they will not so much as take Warning.’ It is easy to take the view that it does not matter greatly if people take neither warning nor advice, and continue to work their way through the Earth’s fossil carbon reserves until they can get no more. As the greenhouse gases build up, more energy will be trapped in the atmosphere, making the planet warmer, altering rainfall distribution and increasing sea level. That icon of climate change, the polar bear, will disappear from its natural home, along with other less spectacular creatures. After very many thousands of years, most of the fossil-derived carbon dioxide will end up in the ocean or in marine sediments and the flux of carbon dioxide between air, sea and land will return to balance. In the meanwhile, many of our descendants could find themselves without the necessities for life. It is also possible to imagine a world where we humans stabilize the climate, deliberately reducing the concentration of greenhouse gases in times of global warming, increasing them when the inexorable swing of the Milankovitch Cycles brings us to the start of another ice age.

Global warming is insidious: it is hard to discern slow long-term trends in climate against the daily, seasonal and annual variations that we all know as the weather. It thus differs from the more obvious and immediate threats facing humanity in the twenty-first century - militarism, fanaticism, political and economic instability, corruption and lethal pandemics.

It is impossible to put a precise figure on how much time we have left to put effective controls on greenhouse gases in place. According to the Stern Review ‘there is still time to avoid the worst impacts of climate change if strong collective action starts now’. Further, ‘the next ten to twenty years will be a period of transition, from a world where carbon pricing schemes are in their infancy, to one where carbon pricing is universal and automatically factored into decision making’. But the longer the delay, the more damage will be done and the more it will cost to remedy. Because so much fossil carbon dioxide has already been emitted, some warming is inevitable, whatever is done in the future, and people will have to adapt to this warming (and to the associated rise in sea level) as best they can.

There are no simple ways to deal with the changes in climate that people are bringing upon themselves. Although no one can say how people will deal with the effect of their own activities in the distant future, certain options are already available. People can adapt to climate change, become less wasteful with energy, work out ways to prevent greenhouse gases entering the atmosphere and develop clean sources of energy. There are good precedents: governments have already acted concertedly and successfully to control chemicals that destroy the ozone layer and to reduce the emission of sulfurous gases from industry. As developing countries such as China, India or Brazil industrialize, more fossil fuel will be used – unless they can leapfrog the carbon phase of development and move comprehensively to non-fossil sources of energy. But no developing country is going to agree to remain poor, just to prevent climate change in other parts of the world.

The most urgent technological problems now facing people (see **Table 5.1)** are to reduce carbon dioxide emissions from electricity generation and heavy industry, to make buildings more energy-efficient and to obtain more kilometres per litre of fuel from transport, particularly cars. The great advantage of fossil fuels is their cheapness and convenience, compared to most alternatives, but fuel costs will rise as demand increases and the more accessible fossil reserves are worked out. This rise in the real cost of fossil fuel, coupled with the dire long-term influence of fossil fuels on climate, will increasingly drive people to investigate and exploit non-fossil sources of energy – assuming that the drive to greener energy is not derailed by accident, obduracy, or vested interests.

Although no legally binding agreements to limit emissions emerged from the 2009 United Nations Climate Change Conference in Copenhagen, the meeting did show that all the major countries now accept that the ever-increasing use of fossil fuels will alter global climate, in most cases for the worse. It would be surprising if universal agreement could be reached at one meeting, seeing the huge differences in development of the different countries involved – and the compexity of their political alliances. But a global problem requires global agreement – at least between the major industrial countries. There is an old Irish saying 'the windy day is not the day to be mending the thatch', and there is much to be said for making such agreements before, rather than after the thatch starts to leak.

The choices between the various ways of dealing with climate change will be made through the evolving interplay of political, regional and economic forces, not by the engineers and scientists to whom this article is addressed. But these scientists and engineers have a duty to point out what is happening and what can be done to mitigate the situation. Their advice must be based on a balanced assessment of the evidence and, crucially, indicate the range of uncertainties in their conclusions. They also have a duty to strive towards objectivity, at the same time openly acknowledging funding and other support. The engineers will, as always, have the task of putting ideas into action and dealing with the problems that arise as they go about their work.

Just in case you need to know:-

The symbol M (for mega) means 10^6; G (for giga) is 10^9, T (for tera) is 10^{12}, P (for peta) is 10^{15} and E (for exa) is 10^{18}.

A joule (J) is the SI unit of work, energy and heat. One joule is the work done when a force of one newton moves its point of application 1 m in the direction of the force.

A watt (W) is the SI unit of power. One watt is one joule per second.

Energy is power multiplied by time. Thus one kWh is the amount of energy equivalent to a steady power of 1 kilowatt running for one hour, or 3.6×10^6 J.

An electricity generating plant rated at one GW, running full-time at its rated output, would produce 31.56 PJ in one year, or 8766 million kWh.

To convert Wm^{-2} to $kWhm^{-2}day^{-1}$ multiply by 0.024

To convert Wm^{-2} to $MJm^{-2}day^{-1}$ multiply by 0.0864

One tonne of carbon dioxide carbon (t CO_2-C) is equivalent to 44/12 or 3.67 tonnes of carbon dioxide. Wherever possible, I have avoided giving the mass of CO_2, but used the equivalent mass of CO_2 *carbon* instead.

One tonne oil equivalent (toe) corresponds to 4.185×10^{10} J or 1.163×10^4 kilowatt-hours. It is a much-used measure of energy, being the amount of energy released when one tonne of crude oil is burned. One barrel of oil contains 42 US gallons or 159.0 litres. There are *approximately* 7.2 barrels in a tonne of oil. A barrel of crude oil contains *approximately* 0.118 tonnes of carbon

One ppm by volume of atmospheric carbon dioxide is equivalent to 2.13 Gt C.

Total concentration of greenhouse gases is given as carbon dioxide equivalent, (or CO_2e). This is the sum of all the long-lived greenhouse gases, each calculated as its carbon dioxide equivalent from its Global Warming Potential over a 100 year time-frame (see **Table 1.1**).

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