Climate Change

Biological and Human Aspects

Jonathan Cowie

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CLIMATE CHANGE: BIOLOGICAL AND HUMAN ASPECTS

In recent years climate change has become recognised as the foremost environmental problem of the twenty-first century, and a subject of considerable debate. Not only will climate change affect the multi-billion dollar energy strategies of countries worldwide, but it could also seriously affect many species, including our own. Written in an accessible style, this textbook provides a broad review of past, present and likely future climate change from the viewpoints of biology, ecology and human ecology. It is thoroughly referenced, allowing readers, if they wish, to embark on their own more specialist studies.

A fascinating introduction to the subject, this textbook will be of interest to a wide range of people, from students in the life sciences who need a brief overview of the basics of climate science, to atmospheric science, geography and environmental science students who need to understand the biological and human ecological implications of climate change. It will also be a valuable reference for those involved in environmental monitoring, conservation, policy-making and policy lobbying.

Jonathan Cowie has spent many years conveying the views of biological science learned societies to policy-makers. His earlier postgraduate studies related to energy and the environment, and he is a former Head of Science Policy and Books at the Institute of Biology (UK). He is author of *Climate and Human Change: Disaster or Opportunity* (Parthenon Publishing, 1998).

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Introduction

This book is about biology and human ecology as they relate to climate change. Let's take it as read that climate change is one of the most urgent and fascinating science-related issues of our time and that you are interested in the subject: for if you were not you would not be reading this now. Indeed, there are many books on climate change but nearly all, other than the voluminous Intergovernmental Panel on Climate Change (IPCC) reports, tend to focus on a specialist aspect of climate, be it weather, palaeoclimatology, modelling and so forth. Even books relating to biological dimensions of climate change tend to be specialist, with a focus that may relate to agriculture, health or palaeoecology. These are, by and large, excellent value provided that they cover the specialist ground which readers seek. However, the biology of climate change is so broad that the average life-sciences student, or specialist seeking a broader context in which to view their own field, has difficulty in finding a wide-ranging review of the biology and human ecology of climate change. Non-bioscience specialists with an interest in climate change (geologists, geographers, atmospheric chemists, etc.) face a similar problem. This also applies to policy-makers and policy analysts, or those in the energy industries, getting to grips with the relevance of climate change to our own species and its social and economic activities.

In addition, specialist texts mainly refer to specialist journals. Very few university or research-institute libraries carry the full range. Fortunately the high-impact factor and multi-disciplinary journals such as *Science* and *Nature* do have specialist climate papers (especially those relating to major breakthroughs) and virtually all academic libraries, at least in the anglophone world, carry these publications. It is therefore possible to obtain a grounding in the biology (in the broadest sense) of climate-change science from these journals provided, that is, one is prepared to wade through several years' worth of copies.

This book hopefully scores with its broad biological approach, its tendency to cite the high-impact journals (although some specialist citations are also included) and its level of writing (hopefully appropriate for junior undergraduates and specialists reading outside their field). It should also be accessible to bioscientists as well as those outside of the life sciences. However, here is a quick word of advice. Familiarise yourself with the appendices at the back before you start reading!

Even so, this book can only be an introduction to the biology and human ecology – past, present and future – of climate change. Readers seeking more specialist knowledge on any particular aspect should seek out the references, at least as a starting point.

This book's style is also different to many textbooks. Reading it straight through from start to finish one may get the feeling that it is a little repetitious. This is only *partly* true. It is true in the sense that there are frequent references to other chapters and subsections. This is for those looking at a specific dimension, be they specialists putting their own work into a broader climate context, students with essays to write, or policy analysts and policy-makers looking at a special part of the human–climate interface. In short, this book is written as much, if not more, for those dipping into the topic as it is as a start-to-finish read.

There is another sense in which this book appears repetitious, although in reality it is not. It stems from one particular problem scientists have had in persuading others that human activity really is affecting our global climate. This is that there is no single piece of evidence that by itself proves such a hypothesis conclusively. Consequently those arguing a contrary case have been able to cite seemingly anomalous evidence, such as that a small region of a country has been getting cooler in recent years or that the Earth has been warmer in the past, or that there have been alternating warm and cool periods. All of this may be true individually but none of it represents the current big picture. So, instead of a single, all-powerful fact to place at the heart of the climate-change argument, there is a plethora of evidence from wide-ranging sources. For instance, there is a wealth of quite separate geological evidence covering literally millions of years of the Earth's history in many locations across the globe. This itself ranges from ice cores and fossils to isotopic evidence of a number of elements from many types of sediment. There is also a body of biological evidence from how species react to changes in seasons to genetic evidence from when species migrated due to past climate change. Indeed, within this there is the human ecological evidence of how we have been competing with other species for resources and how this relates observed changes in both human and ecological communities with past climate change.

This vast mass of evidence all points to the same big picture of how changes in greenhouse gases and/or climate have affected life in the past. Then again there is the present and the evidence used to build up a likely picture of what could well happen in the future. Here again, the evidence seems to be very largely corroborative. Therefore, to readers of this book it can seem as if the same ground is being covered when in fact it is a different perspective being presented each time that leads to the same concluding picture.

Indeed, because there is so much evidence contributing to the big picture, some may well find that evidence from their own specialist area of work is not included, or, if it is included, is covered briefly. This is simply because the topic is so huge and not due to a lack of recognition on my part of the importance of any particular aspect of climate-change science.

That there are similar themes running through specialist areas of climate-change science and the relating biology is in once sense comforting (we seem to be continually improving our understanding and coming to a coherent view) but in another it is frustrating. Over the years I have spoken to a large number of scientists from very disparate disciplines. Part of this has been due to my work (policy analysis and science lobbying for UK learned societies and before that in science journal and book management) and in part because I enjoy going to biosphere science as well as energy-related symposia. (There is nothing quite like looking over the shoulders of a diverse range of scientists and seeing what is happening in the laboratory and being discovered in the field.) The key thing is that these individual specialist, climate-related scientists all tend to say similar things, be they involved with ocean circulation, the cryosphere (ice and ice caps), tropical forests and so forth. They say the same as their colleagues in other specialist areas but equally do not appear to really appreciate that there is such a commonality of conclusion. For example, a common emerging theme is that matters are on the cusp. Change is either happening or clearly moving to a point where (frequently dependent on other factors) marked change could well happen. It is perhaps a little disappointing that more often than not such specialists seem to have a limited awareness of how their counterparts in other disciplines view things. (I should point out that, in my view, this has more to do with pressures from how science is undertaken these days, and not due to the high level of competence these specialists have within their own field. Scientists simply are not afforded the time to take several steps back from their work and view the larger scientific panorama.) That science is so compartmentalised tends to limit wide-ranging discussions, yet these, when properly informed by sound science, can be exceptionally fruitful.

By now you may be beginning to suspect what has been motivating my researching and writing of this book. The question that remains for me is whether this book will have any effect on your own motivations and understanding? As it is quite likely that I will encounter at least some of you over the coming years, I dare say I will find out. Meanwhile, I hope you find this topic as fascinating as I do.

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I would very much like to thank all those in UK bioscience with whom I have interacted in some way or other on climate-change matters. In particular, I should thank a good number who have been on the various Institute of Biology science committees since the 1990s. This also goes to a score or two of my fellow members of the British Ecological Society and the Geological Society of London. A special thank you goes to those who have alerted (and, as often as not, invited) me to workshops and symposia on climate and energy issues as well as on biosphere science. I have found every one useful in at least one way: many provided a number of new insights and all gave me a reality check. Thank you.

This book also owes a lot to some research bodies. In the UK we are quite bad at making data from tax-payer-funded research publicly available (even for education and policy purposes). This is not so in the USA and so I greatly valued the open access that the National Oceanic and Atmospheric Administration give to their palaeoclimate-related data (which I have used to generate a number of the figures). Interested readers can visit their website at www.ncdc.noaa.gov/oa/ncdc.html. I am also extremely appreciative of the UK Environment Agency's current (2006) Chief Executive, without whom Figure 6.5 simply would not have been presented! Then there are the many who sent paper off-prints (e-mailed pdf files). There are too many to mention but be assured all are referenced.

Talking of references, as mentioned in the Introduction as far as possible I have taken either major reports, many of which are available on the Internet, or used high-impact-factor journals that can be found in most university libraries (these in turn cite papers in more specialist publications). However, I have also used a number of World Health Organization (WHO) press releases. This comes from my background in science policy, and the WHO have been sending me these for the best part of two decades. You will not find these in university libraries but fortunately you too can seek these out, on www.who.int/mediacentre/news/en.

A mention also has to go to the friendly and helpful librarians of Imperial College London, whose work really is appreciated. Then there are all those who have facilitated my site and field visits in the UK and abroad, be they to power stations (fossil, hydroelectric and nuclear), sites of special scientific interest (in the literal and not just the UK technical sense of the term) and educational institutions.

A thank you also goes to Peter Tyers for the cover picture. This is the second time he has done this for me, but then he is a good photographer.

Finally I must specifically thank Cambridge University Press and freelance copy-editor Nik Prowse for work on the manuscript. I like to think that I have long since found my feet with words, but any capability for editorial spit and polish has always eluded me. Nik has also greatly helped standardise the referencing and presentation. I therefore really do value good editors (and so should you) and especially those who appreciate those who try to do things a little differently. With luck you will notice.

1

An introduction to climate change

In most places on this planet's terrestrial surface there are the signs of life. Even in those places where there is not much life today, there are frequently signs of past life, be it fossils, coal or chalk. Further, it is almost a rule of thumb that if you do discover signs of past life, either tens of thousands or millions of years ago, then such signs will most likely point to different species to those found there today. Why? Here there are a number of answers, not least of which is evolution. Yet a key feature of why broad types of species (be they broad-leaved tree species as opposed to narrow needle-leaved ones) live in one place and not another is to do with climate. Climate is a fundamental factor influencing biology. Consequently a key factor (among others) as to why different species existed in a particular place 5000, 50 000, 500 000 or even 5 000 000 years ago (to take some arbitrary snapshots in time) is due to different climatic regimens existing at that place in those times.

It is also possible to turn this truism on its head and use biology to ascertain aspects of the climate, and biological remains are aspects of past climates. Furthermore, biology can influence climate: for example, an expanse of rainforest transpires such a quantity of water, and influences the flow of water through a catchment area, that it can modify the climate from what it otherwise would have been in the absence of living species. Climate and biology are interrelated.

Look at it another way. All living things flourish within a temperature range as well as have certain temperature tolerances for aspects of their life cycle. Furthermore, all living things require a certain amount of water and the availability of water, terrestrially, is again driven by climate. Given this essential connection of temperature and water to life, it is not difficult to see how important climate is in determining where different species, and assemblages thereof (ecosystems), can be found.

From this we can easily deduce that if climate is so important, then climate change is absolutely critical if we are to predict the likely fate of species in a certain region. It is also possible to use the reverse in an applied sense to note the presence (or past presence) of different species and then use this as an indicator of climate, both in the past and in the present. This interrelationship between life and climate is fundamental. It affects all species, which includes, we sometimes forget, our own – *Homo sapiens*. Here we also tend to forget that on every continent except Antarctica there are examples of deserted settlements and evidence of long-extinct civilisations. These are societies that once flourished but have now gone, due primarily to a change in climate.

If it is not sufficiently significant that living things, including human societies, are subject to the vagaries of climate change, there is now convincing evidence that our modern global society is currently altering the global climate in a profound way that also has regional, and indeed global, biological implications that will impact heavily on human societies. For these reasons there is currently considerable interest in the way living things interact with the climate, and especially our own species. As we shall see in the course of this book, biology, and the environmental sciences relating to ecology and climate, can provide us with information as to past climates and climate change (palaeoclimatology) which in turn can illuminate policy determining our actions affecting future climate. This will be invaluable if we are to begin to manage our future prospects.

1.1 Weather or climate

Any exploration of the biology of climate change needs to clarify what is meant by climate as distinct from weather. In essence the latter is the day-to-day manifestation of the former. The climate of a region is determined by long-term weather conditions including seasonal changes. The problem is that weather is in its own right a variable phenomenon: if it were not we would have less difficulty in arriving at more accurate long-term forecasts. Consequently, if the climate of a region changes we can only discern this over a long period of time once we have disentangled possible climate change from weather's natural background variability. Analogously, physicists and engineers refer to what they call the signal-to-noise ratio, and this they apply to electrical currents or an electromagnetic signal, be it a commercial radio broadcast or that from a stellar body. Similarly with climate change, the problem is to disentangle a small climatic-change signal from considerable background weather noise. For example, one very hot summer (or drought, or heavy monsoon, or whatever...) by itself does not signify climate change. On the other hand, a decade or more of these in succession may well be of climatic significance.

Before we explore climate change and especially current problems, we first need to be aware of some terms and the phenomena driving current global warming.

1.2 The greenhouse effect

The greenhouse effect is not some peripheral phenomenon only of importance to global warming. The greenhouse effect is at the heart of the Earth's natural climatic systems. It is a consequence of having an atmosphere, and of course the atmosphere is where climates are manifest.

The French mathematician Jean-Baptiste Joseph Fourier (not to be confused with the contemporary chemist of the same name) is generally credited with the discovery of the greenhouse effect. He described the phenomenon, in 1824 and then again in a very similar paper in 1827 (Fourier, 1824, 1827), whereby an atmosphere serves to warm a planet. These papers almost did not get written as Fourier was very nearly guillotined during the French Revolution and only escaped when those who condemned him were ultimately guillotined themselves.

Perhaps the best way to illustrate the greenhouse effect is to consider what it would be like if the Earth had no atmosphere. This is not as difficult as it might first seem. We only have to travel 384 400 km (238 856 miles) to the Moon and see the conditions there. On that airless world (its atmosphere is barely above vacuum at one trillionth (10^{-12}) of the Earth's) the daytime temperature is 390 K (117 °C), while at night it drops to 100 K (−173 °C), giving a median of some 245 K (−28 °C). During the lunar day, sunlight is either reflected off the Moon's rocky surfaces or is absorbed, warming the rocks that then re-radiate the energy. The total amount of incoming radiation equals that outgoing. However, at the Earth's surface the average global temperature is higher, at about 288 K (15 °C). The Earth's atmosphere keeps the planet warmer than it would otherwise be by some 43 K (43 °C). This 43-K warming is due to the Earth's atmospheric greenhouse. It is perfectly natural. This warming effect has (albeit to a varying extent) always existed. It occurs because not all the thermal radiation from the Sun falling on our planet's surface gets reflected back out into space. The atmosphere traps some of it just as on the Moon rock is warmed. However, more is trapped on Earth because the atmosphere is transparent to some frequencies (the higher frequencies) of thermal radiation, while opaque to some other, lower, frequencies. Conversely, rock on the Moon is not at all transparent so only the surface of the rock warms and not the strata deep beneath.

The reason why some of the light reflected from the Earth's surface, or radiated as infrared radiation from the lower atmosphere, becomes trapped is because it has changed from being of the sort to which the atmosphere as a whole is transparent to that to which the atmosphere is opaque. There are different types of light because photons of light can be of different energy. This energy (E) of electromagnetic radiation (light, thermal radiation and other rays) is proportional to its frequency (ν) or colour, with the constant of proportionality being Planck's constant (h, and which is estimated to be 6.626×10^{-34} J s). And so the atmosphere is transparent to some frequencies of light but not others. This transparency mix allows some higher-energy light into the blanket of atmosphere surrounding our planet, but hinders other, especially lower-energy infrared (heat-level), wavelengths from getting out. The exact mathematical relationship between the energy of a photon of light (or any other electromagnetic radiation) was elucidated, long after Fourier, in 1902 by the German physicist Max Planck. It can be expressed in the following simple equation.

$$E = h\nu.$$

E (energy) is measured in joules and ν (frequency) in hertz.

When sunlight or solar radiation is either reflected off dust particles and water droplets in the atmosphere, or alternatively off the ground, it loses energy. As a result of the above relationship between energy and frequency, this reflected light is now at a lower energy, hence lower frequency. As stated, the atmosphere, while transparent to many higher frequencies, is opaque to many of the lower thermal frequencies. The atmosphere traps these and so warms. Consequently the atmosphere acts like a blanket trapping lower-frequency radiation (see Figure 1.1). It functions just as the glass of a greenhouse does by allowing in higher-frequency light, but trapping some of the lower-frequency heat; hence the term greenhouse effect. This is why those constituents of the atmosphere that strongly exhibit these properties are called greenhouse gases. The Irish polymath John Tyndall described the greenhouse role of some gases in 1861 (Tyndall, 1861) and succeeded in quantifying their heat-absorbing properties.

There are a number of greenhouse gases. Many of these occur naturally at concentrations determined by natural, as opposed to human, factors. Water vapour (H_2O) is one, methane (CH_4) another, as is nitrous oxide (N_2O), but the one most frequently talked about is carbon dioxide (CO_2). Others do not occur naturally. For example, halocarbons such as CFCs (chlorofluorocarbons) are completely artificial (human-made), being products from the chemical industry that are used as coolants and in foam blowing. Then again, today there are the naturally occurring greenhouse gases, like carbon dioxide, whose atmospheric concentrations are further enhanced by human action.

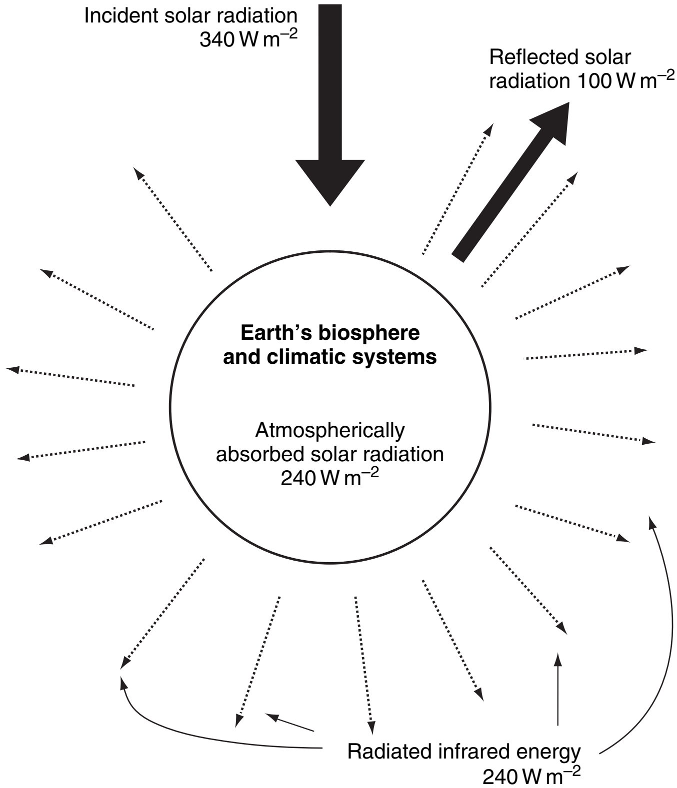

Figure 1.1 A summary of the principal solar-energy flow and balance in the Earth's atmosphere. Not all the high-energy infrared radiation falling on the Earth is reflected back out into space. Some is converted into lower infrared energy in the atmosphere. The result is atmospheric warming. Note: the Sun radiates 1370 W m^{-2} to the Earth's distance. However, the Earth is a rotating sphere not a flat surface, so the average energy falling on the Earth's surface is just 340 W m^{-2}.

Tyndall not only recognised that there were greenhouse gases, he also speculated what would happen if their concentration in the atmosphere changed. He considered what it would be like if their warming effect did not take place (as on the Moon). Indeed, he contemplated that a reduction in greenhouse gases might throw the Earth into another ice age. Strangely though, he never considered what might happen if the concentration of greenhouse gases increased. Consequently he *never* asked what would happen if human action contributed additional greenhouse gases. In other words, what would happen if there was the addition of an anthropogenic contribution to the natural greenhouse effect?

It is this difference, between the natural greenhouse effect and the additional human-generated (anthropogenic) effect, which is at the heart of the current issue of global warming. The Swedish chemist and Nobel laureate Svante August Arrhenius first proposed that the human addition of carbon dioxide to the atmosphere would result in warming in 1896, although he himself did not use the term greenhouse but hothouse.

Today the atmosphere is indeed changing, as Arrhenius thought it might, with the concentration of carbon dioxide increasing in recent terms largely due to the burning of fossil fuels. In 1765, prior to the Industrial Revolution, the Earth's atmosphere contained 280 ppm (parts per million) of carbon dioxide. By 1990 (which is, as we shall see, a key policy date) it contained 354 ppm and was still rising. By 2005 it had topped 380 ppm and was still climbing.

Over this time the Earth has also warmed. The warming has not been as regular as the growth in greenhouse gas but, from both biological and abiotic proxies (of which more later) as well as some direct measurements, we can deduce it has taken place. Furthermore, we now know that Tyndall was right. With less greenhouse gas in the atmosphere the Earth cools: there are ice ages. As we shall see (in Chapter 3) we have found that during the last glacial period, when the Earth was cooler, there was less atmospheric carbon dioxide.

Nonetheless there has been much debate as to whether the current rise in atmospheric carbon dioxide has caused the Earth to warm. An alternative view is that the warming has been too erratic and is due to random climate variation. To resolve this issue the United Nations (UN), through the UN Environment Programme (UNEP) and World Meteorological Organization (WMO), established the Intergovernmental Panel on Climate Change (IPCC). Its three main reports or assessments (Intergovernmental Panel on Climate Change, 1990, 1995, 2001a, 2001b) have concluded that the 'emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate'.

The current rise in atmospheric greenhouse gases (over the past three centuries to date) is well documented and is summarised in Table 1.1.

Table 1.1. *Summary of principal greenhouse gases (with the exception of tropospheric ozone (O_3) due to lack of accurate data). Atmospheric lifetime is calculated as content/removal rate.*

Greenhouse gas...	CO_2	CH_4	CFC-11	CFC-12	N_2O
Atmospheric concentration					
Late 18th century	280 ppm	0.7 ppm	0	0	288 ppb
2001	371 ppm	1.75 ppm	252 ppt	480 ppt	315 ppb
Atmospheric lifetime (years)	50–200	12	45	130	114

ppb, parts per billion; ppm, parts per million; ppt, parts per trillion.

As we shall see, each of the above greenhouse gases contributes a different proportion to the human-induced (anthropogenic) warming, but of these the single most important gas, in a current anthropogenic sense, is carbon dioxide.

There are two reasons for the different warming contributions each gas makes. First, the concentrations and human additions to the atmosphere of each gas are different. Second, because of the physicochemical properties of each gas, each has a different warming potential.

With regards to changes to the various present-day concentrations of the different gases, they are due to the post-Industrial Revolution increases in each gas: human influences on the global atmosphere were very different before the Industrial Revolution. The changes in the concentration of these key greenhouse gases each largely arise from different sets of human actions. For instance, part of the increase in carbon dioxide comes from the burning of fossil fuels and part from deforestation and changes in land use. Again, some of the increase in methane comes from paddy fields, while part of the rest comes from the fossil-fuel industry and biomass burning. We shall examine this in more detail in the next section when looking at the carbon cycle, but other methane increases (or, in the pre historic past, decreases) are due to more complex factors such as the climate itself, which can serve to globally increase, or decrease, the area of methane-generating wetlands.

Both carbon dioxide and methane are part of the global carbon cycle (see the following section). Nitrous oxide (N_2O) forms part of the nitrogen cycle and, like carbon dioxide and methane, has both natural and human origins. Naturally, nitrous oxide is given off by the decomposition of organic matter in soils, in particular by tropical forest soils that have high nutrient-cycling activity, as well as by oceans. Human sources include biomass burning and from the use of fertilisers. The principal agent removing nitrous oxide from the atmosphere is photolysis – removal by the action of sunlight – ultimately resulting in nitrogen (N_2) and oxygen (O_2).

As to the second factor determining the different warming contribution each gas makes, each has different physicochemical properties. These are quantified for each gas in what is called their global warming potential (GWP). GWPs are a comparative index for a unit mass of each gas measured against the warming potential of a unit mass of carbon dioxide *over a specific period of time*. Carbon dioxide has, therefore, a defined warming potential of 1. A complicating factor is that because different greenhouse gases have different atmospheric residence times (see Table 1.1) GWPs *have* to relate to a specific time frame. A GWP expressed without a time frame is nonsense. This can be understood by considering methane, which only has an average atmospheric

Table 1.2. *Global warming potentials (GWPs) for some of the principal greenhouse gases over three time frames (IPCC, 2001a).*

Gas	Atmospheric lifetime (years)	GWP Time horizon . . . 20 years	100 years	500 years
Carbon dioxide	50–200	1	1	1
Methane	12	62	23	7
Nitrous oxide	114	275	296	156

residence time of a dozen years. Nearly all of a kilogram of methane will still be in the atmosphere after a year. Roughly half of it will be in the atmosphere after 12 years and, assuming exponential decay, a quarter or less after 24 years. Conversely nitrous oxide has an average residence time of over a century. So, clearly, comparing the GWPs of nitrous oxide and methane over a decade will give different warming figures compared with the same comparison over a century. Finally, because of uncertainties, not least with carbon dioxide's own atmospheric residence times, different researchers have different GWP estimates. This can be especially frustrating, as estimates 'improve' with time or as different theories as to the dominating effect of, for example an aspect of the carbon cycle, come into vogue, it means that GWPs often vary both with research team and with time. Even the IPCC's GWP estimates vary a little from report to report. Furthermore, because the IPCC is science by committee – where uncertainty is resolved through consensus of opinion – one cannot simply dismiss one research team's estimates as being completely out of hand. Instead, when looking at a research team's climatic model, you need to see what GWP estimates are used as well as the model itself and then make your own judgement on its results compared to those of another team. Table 1.2 summarises the IPCC's 2001a estimates for GWPs for carbon dioxide, methane and nitrous oxide. CFCs (chlorofluorocarbons) and HFCs (hydrofluorocarbons) are not included as there are so many different ones. However, typically most have GWPs of a few thousand (compared to carbon dioxide's GWP of 1) for time horizons up to 500 years. Fortunately because of their low atmospheric concentration, human-made chemicals such as CFCs and HFCs contribute less than a quarter of current warming (see Figure 1.2).

There is one important greenhouse gas that has only briefly been mentioned so far, and that is water vapour. Water vapour is a powerful greenhouse gas contributing a significant proportion of the natural (as opposed to the human-induced) greenhouse effect. There is sufficient water vapour above the troposphere for it to absorb much of the infrared radiation at its absorptive

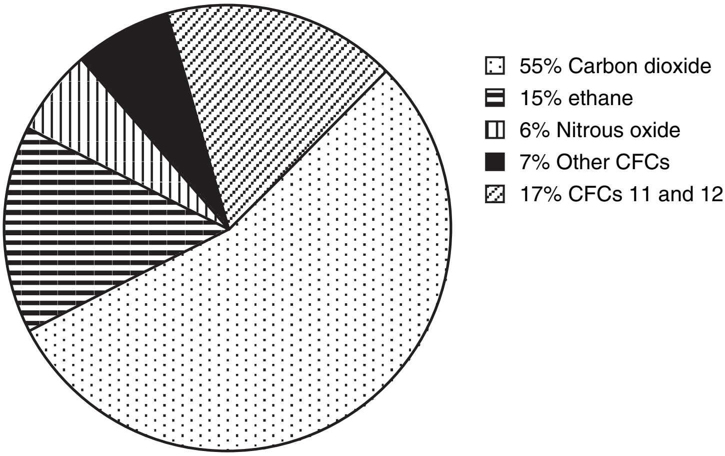

Figure 1.2 The contribution from each of the principal anthropogenic greenhouse gases due to the change in warming (radiative forcing) from 1980 to 1990 (excluding ozone, which may or may not be significant and is difficult to quantify). Data from IPPC (1990).

frequencies. Indeed, if we were to look at the Earth from space, solely in water-vapour frequencies, our planet would appear as mist-veiled as Venus. This is true even over the dry Sahara Desert. But the concentration of water vapour is not consistent throughout the entirety of the atmospheric column. Tropospheric water vapour, in the atmospheric layer closest to the ground, varies considerably over the surface. In the first 1–2 km of the atmosphere (in the lower part of the troposphere), the amount of water vapour in a unit volume increases with temperature. In the troposphere above this point, the water-vapour greenhouse effect is most important and harder to quantify. Furthermore, current computer models of the global climate account for water-vapour feedback, whereby a warmer world sees more evaporation, hence more water vapour, and this tends to double the warming that one would expect from just a fixed-water-vapour model. The ability of current (early twenty-first century) global climate computer models to reproduce the likely effect of water vapour over a period of warming was given credence in 2005 by a US team of atmospheric scientists led by Brian Soden. They compared satellite observations between 1982 and 2004 at the 6.3 μm wavelength, which is part of water's absorption spectrum and especially useful for measuring its presence in the upper troposphere, and climate models. The satellite measurements and the models showed a good correlation.

Clouds (the suspension of fine water droplets in regions of saturated air) complicate the picture further still. Being reflective they tend to cool the surface during the day and at night act as an effective greenhouse blanket.

However, there are clouds and there are clouds. The picture is complex and our understanding incomplete, hence climate models are only an approximation of what is going on, but revealing approximations nonetheless. (We will return to climate change and the water cycle later in this chapter.)

Given that overall the Earth's atmosphere is broadly conferring a 43 °C greenhouse warming effect (since, as we have seen, the airless Moon is cooler), the question remains as to how much warming has been conferred anthropogenically since the Industrial Revolution, due to the human addition of greenhouse gases. We shall come to this in Chapter 5. Nonetheless it is worth noting for now that mathematicians Cynthia Kuo and colleagues from the Bell Laboratory, New Jersey, USA, statistically compared instrumentally determined changes in atmospheric CO_2 concentrations between 1958 and 1989 and global temperature (Kuo *et al.*, 1990). This confirmed that carbon dioxide and global temperature over that period were significantly correlated to over 99.99%. This is to say that were 10 000 alternative copies of the Earth similarly measured that only one would give similar results due to sheer chance and 9999 would give results because there is a link between carbon dioxide concentrations and global temperature. But before looking at how the human addition of carbon dioxide to the atmosphere affects climate we need a better understanding of atmospheric carbon dioxide's natural sources and sinks. Fundamental to this is the carbon cycle.

1.3 The carbon cycle

Carbon is one of the fundamental elements necessary for life. It is found in virtually all molecules (but not quite every molecule) associated with life. These include all carbohydrates, all proteins and all nucleic acids. As such, carbon is fundamental to biological structures, of both micro- and macro-organisms, including plants and animals; for example, lignin in plants and cartilage and bone in animals. Indeed biomolecules, as we shall see (Chapter 2), can be of great use to palaeoclimatologists as some of them (and hence the remains of species in which they are found) can be used as climatic indicators.

The carbon cycle itself refers to the circulation of carbon in the biosphere. The circulation is driven primarily (but not solely) by biological processes. A planet that does not have any biological processes sees carbon flows through its geosphere driven solely by geophysical processes. On Earth carbon, in the form of carbon dioxide, is fixed by photosynthesis into organic compounds in plants and photosynthetic algae and returned to the atmosphere mainly by the respiration of plants, animals and micro-organisms in the form of carbon dioxide, but also by the decay of organic material in the form of both methane and carbon dioxide. Abiotic drivers include the burning of organic material, be it natural (e.g. forest fires) or through human action (e.g. the burning of firewood or fossil fuels). Another abiotic driver is that of plate-tectonic movement. This contributes to the so-called deep carbon cycle operating on a scale of millions of years. Here plates in the process of subduction carry with them organic sediments down into the Earth's mantle. This plate movement results in volcanic activity that in turn converts the organic sediments to carbon-containing gases (again mainly carbon dioxide but also other volatile compounds) that come to the surface via volcanic and related activity. There are a variety of other abiotic processes including the chemical oxidation of methane in the atmosphere to carbon dioxide as well as processes (which frequently also accompany biotic ones) in organic sediments. An estimate of the principal carbon movements within the carbon cycle is given in Figure 1.3.

The carbon cycle is at the centre of biology's relationship with the global climate (and hence global climate change). More than this, it demonstrates the

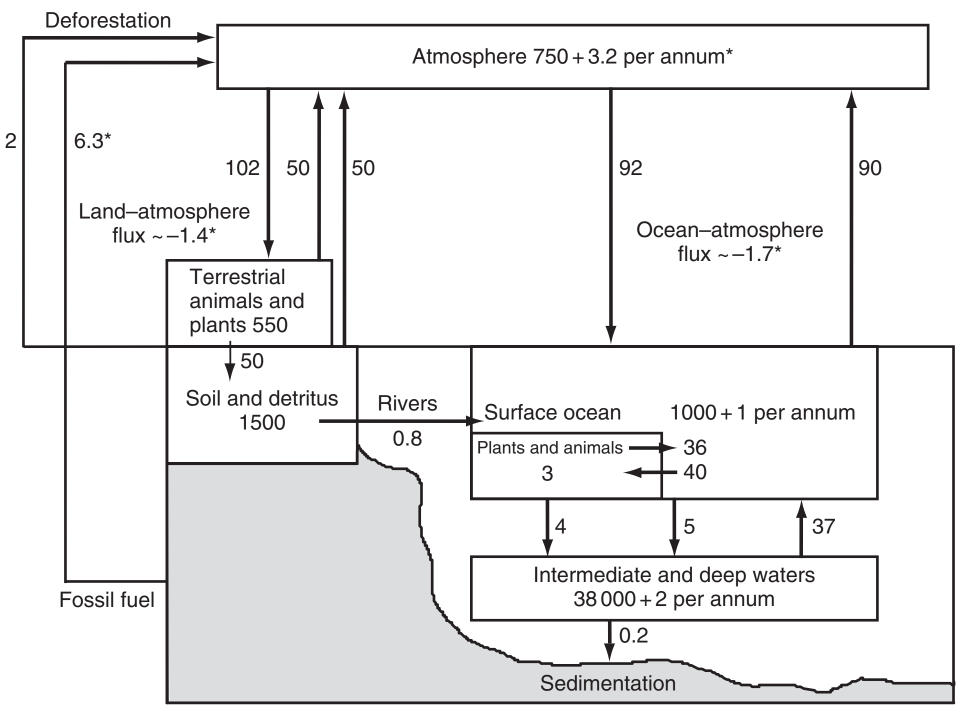

Figure 1.3 Broad estimates of the principal carbon sources and sinks in gigatonnes of carbon (GtC) as well as approximate movements of carbon about the carbon cycle in gigatonnes of carbon per annum (GtC $year^{-1}$). It is important to realise that there are a number of uncertainties that are the subject of current research (see text). The figure includes 2001 IPCC estimates for annual fluxes (1990–1999), marked *.

importance of both the new molecular biological sciences as well as the whole-organism approach to biology.

A first impression of the biology associated with the carbon cycle might focus on the plant activity sequestering carbon dioxide from the atmosphere. But this is just one aspect, albeit a key one. There is also plant and animal respiration, and the respiration of bacteria and fungi, returning carbon dioxide to the atmosphere. We might also think of biomes (climatically determined regional groups or assemblages of ecosystems) and how these might affect the global carbon cycle in terms of marine productivity or of the carbon in a biomes' biomass, be it in terrestrial tropical rainforests, temperate wetlands, etc. We might also consider the effect of climate change on such ecosystem assemblages as well as individual ecosystems; and indeed we will later in the book. But there is also the biomolecular dimension.

Included in the biomolecular perspective is the role enzymes play. Rubisco (ribulose-1,5-bisphosphate carboxylase oxygenase, which is sometimes portrayed in print as RuBisCO) is the most common enzyme on the planet and is fundamental to photosynthesis. It is therefore probably the most common protein on Earth; it constitutes about half of leaf proteins and is synthesised in chloroplasts. All carbon dioxide captured by photosynthesis – be it in algae or multicellular plants – is handled by this one enzyme. That is about 200 billion t (or 200 Gt) of carbon a year! Another important enzyme is carbonic anhydrase, which catalyses the hydration of about a third of the carbon dioxide in plants and in soil water. As we shall see, the way these enzymes handle carbon dioxide molecules with different isotopes of carbon, or oxygen with different isotopes of oxygen, help us in our understanding of carbon-cycle details.

It is important to note that there are some uncertainties in the estimates of the rate of flows between the various sources and sinks (Figure 1.3). This is the subject of on-going research. Part of the problem (other than the cycle's complexity) is that the carbon cycle is not static: there are varying transfers of carbon, so altering the amounts within reservoirs. For example, during cold glacial times (such as 50 000 years ago) the amount of atmospheric carbon (as both carbon dioxide and methane) was less than today. Conversely, currently the atmospheric carbon reservoir is increasing. This dynamism is not just because of human action; it also happens naturally, although human action is the current additional factor critical to what is called global warming.

In practical terms today, carbon-cycle uncertainties manifest themselves in a number of ways. Of particular concern is the mystery as to where roughly half the carbon dioxide released into the atmosphere by human action (from fuel burning and land-use change) ends up: from measuring the atmospheric concentration of carbon dioxide we know that half of what we burn does not

Table 1.3. *Estimated annual carbon emissions in 1980–9 and 1990–9 to the atmosphere and annual transfer from the atmosphere to sinks (IPCC, 2001a).*

	Carbon transfer (Gt of carbon year^{-1})	
	1980–9	1990–9
From fossil fuels to atmosphere	5.4 ± 0.3	6.3 ± 0.4
From deforestation and land-use change to atmosphere	0.2 ± 0.7	1.4 ± 0.7
Accumulation in atmosphere	3.3 ± 0.1	3.2 ± 0.1
Uptake by ocean	1.9 ± 0.6	1.7 ± 0.5
Net imbalance in estimates	0.4 ± 1.7	2.8 ± 1.7

remain for very long in the atmosphere. This imbalance is so significant that there is debate as to whether a major carbon-cycle process has been overlooked. Alternatively it could be that the current estimates as to the various flows have a sufficient degree of error that cumulatively manifests itself as this imbalance.

The broad (IPCC, 2001a) estimates (together with estimates of uncertainty) as to the contributions of burning fossil fuels and deforestation to atmospheric carbon dioxide as well as the entry to carbon sinks from the atmosphere for the decades 1980–9 and 1990–9 are listed in Table 1.3. The estimates are derived from a computer simulation.

As we can see from Table 1.3 there is this net imbalance between the estimates of carbon dioxide entering and of those accumulating and leaving the atmosphere. More carbon dioxide is being released into the atmosphere than is retained by the atmosphere or thought to be absorbed by the oceans. Where is this carbon dioxide going? This net imbalance is both large and of the same order of magnitude as existing global flows. This is why some think that a major route of carbon from the atmosphere has not been identified, or alternatively that one or more of the existing carbon-flow estimates (Figure 1.3) is considerably off the mark, or perhaps a bit of both. As regards the flow of fossil-fuel carbon to the atmosphere, this is quite well documented due to the economic attention paid to the fossil-fuel industry: we know how many barrels of oil are sold, tonnes of coal are mined, etc. So we can be fairly certain that this estimate is broadly accurate.

Looking at the other side of the equation, the accumulation of carbon in the atmosphere is also accurately charted as it can be, and has been, directly monitored over many years from many locations. It is because we know exactly how much extra carbon we release, and have released, from fossil fuels into the atmosphere as well as how much actually stays in the atmosphere, that we can be certain that there is a shortfall and so that some part of the carbon cycle has either not been properly quantified or even perhaps not properly identified.

It is uncertainties such as this, and that the global climate-warming signal had to be sufficient to be discernable from the background natural variation (noise), that has helped some argue that global warming is not taking place. As we shall see over the next few chapters, the climate has changed in the past (affecting biology and vice versa) and the atmospheric concentrations of greenhouse gases have played a major part in these changes.

Interestingly, the current year-on-year accumulation in atmospheric carbon dioxide, as measured in either the northern or southern hemisphere, is not smooth. Rather, there is an annual oscillation superimposed on the rising trend. The oscillation occurs because of seasonality outside of the tropics. During winters in the temperate zone there are no leaves on the trees and in the boreal zone too there is little photosynthesis on land or in the sea (in the main by algae). But in the summer there is considerable photosynthesis and so more carbon dioxide is drawn into plants and algae. In winter respiration continues, even though photosynthesis is reduced and so, on balance, more carbon dioxide is released into the atmosphere. So there is this annual cycle of waxing and waning of atmospheric carbon dioxide in the northern and southern hemispheres (see Figure 1.4). Indeed, because while in one hemisphere there is summer and the other winter, the carbon dioxide oscillations in the two hemispheres are opposite and complement each other. However, the seasonal variation of carbon dioxide in the southern hemisphere is not nearly so marked, as the southern hemisphere is dominated by ocean, which has a strong ability to buffer carbon dioxide. Oxygen, as the other gas concerned with photosynthetic and respiration reactions, also shows a seasonal variation in each of the hemispheres but one that is more marked than that for carbon dioxide (as oxygen does not buffer in the seas). Like carbon dioxide, the seasonal variation of the atmospheric concentration of oxygen is equal and opposite in the northern and southern hemispheres.

The changes in the atmospheric reservoir of carbon are quite well understood (even though our knowledge of other reservoirs is not so complete) because we can measure atmospheric carbon dioxide directly, and because atmospheric mixing within hemispheres is reasonably thorough. We can therefore be quite certain that our knowledge of this atmospheric part of the carbon cycle is fairly accurate. The problem of the missing carbon seems to be associated with one or more of the other carbon sinks: possibly the accumulation of carbon by terrestrial plants, or alternatively by absorption into the

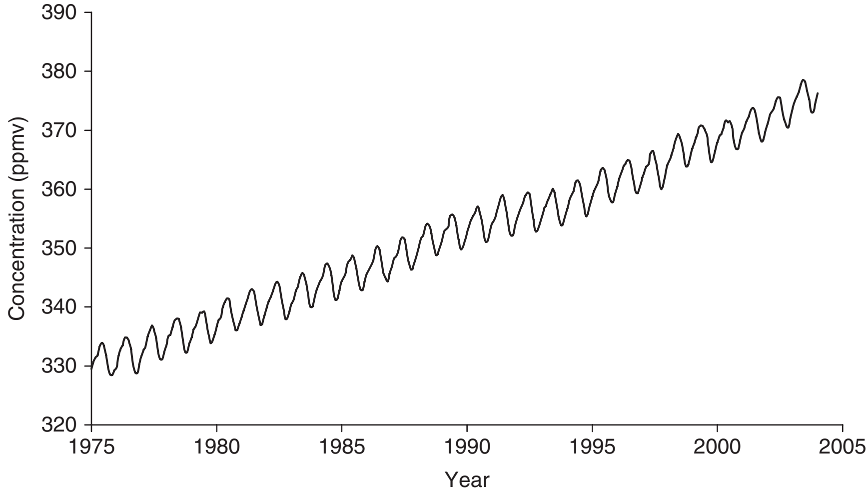

Figure 1.4 Outline of hemispheric seasonality effects of atmospheric carbon dioxide concentration of the late 1970s through to the early twenty-first century. Note that in addition to the annual waxing and waning, there is also an overall trend of growth in atmospheric concentration. ppmv, parts per million by volume.

oceans. Nonetheless, the annual waxing and waning of atmospheric carbon dioxide does illustrate the power of the photosynthetic carbon pump (the power of plant and algal photosynthesis to drive the carbon cycle).

Turning to human impacts on terrestrial reservoirs of carbon, estimates of deforestation do have greater error associated with them than changes in atmospheric gas concentrations, which can be directly measured. So it may well be that part of the missing carbon flow in the carbon cycle is associated with this component of the cycle. However, instances of more detailed scrutiny of deforestation data have revealed that official estimates are invariably underestimates, and that deforestation probably accounts for a greater contribution to atmospheric carbon dioxide, not less, and so the amount of missing carbon is greater. This means that, if anything, our understanding of the cycle's carbon imbalance is not even as good as we think. Of course, deforestation is but one dimension, of a number, to the changes of the terrestrial reservoirs of carbon.

The importance and power of the photosynthetic pump driving part of the carbon cycle is corroborated by the magnitude of the seasonal oscillation in carbon dioxide. Nonetheless land-use change, along with terrestrial-biome change, as well as ocean accumulation, are key areas of uncertainty (either singly or together) that might account for the missing carbon. It could be that oceans are accumulating more carbon than we think and/or that the increased atmospheric carbon dioxide along with global warming is encouraging terrestrial photosynthesis, drawing down carbon into plants over much of the globe. As stated above, because of the magnitude of seasonal variation in atmospheric carbon dioxide outside of the tropics we can see how powerful the photosynthetic and respiratory carbon pumps truly are. *If* this missing carbon sink is terrestrial (and given that much of the planet's land is in just one, the northern, hemisphere) it appears that the carbon may be being sequestered not in a temporary way by annual plants but in a longer-term way by perennials, and especially temperate and boreal trees. Then there is the carbon stored in soils and detritus. The total carbon store in soils, at 1500 GtC, is over twice that stored as biomass and is also more than the atmospheric carbon reservoir. Currently the reservoir of soil carbon is a net sink, although carbon flows to and from it are far less than those to and from either biomass carbon or atmospheric carbon reservoirs. It is important to note that *currently* soil acts as a global net carbon sink. 'Currently' because a world that is just a few degrees warmer could see the soil reservoir act as a net source of carbon as it would be released as carbon dioxide into the atmosphere. In such an instance soils would act to further global warming. (We will return to carbon in soils later in this chapter and again in Chapters 5 and 7.)

Again, as previously mentioned, alternatively (or in addition – we just do not know) the oceans could be a greater sink of carbon than we realise, so they could account for the carbon imbalance. Either way, it is almost certain that the driving force behind this missing sequestration of additional atmospheric carbon is photosynthesis, even if we are unable to say whether it is marine or terrestrial, let alone where on Earth it is taking place.

With regard to the scale of carbon flow between carbon-cycle reservoirs due to photosynthesis, the annual natural seasonal variation in atmospheric draw-down and replenishment we observe is considerable, and it is greater than the year-on-year increasing trend due to the human addition of fossil fuels and land-use change. So just as human action (the action of just one species) is responsible for the current growth in atmospheric carbon dioxide, so one of the most fundamental biological processes – photosynthesis – (through many species) can almost certainly be involved in its amelioration. Again this emphasises that biology and climatology are closely entwined.

Here the ways that photosynthetic and respiratory enzymes handle carbon and oxygen are beginning to illuminate the problem of missing carbon. As stated above, Rubisco is the enzyme globally responsible for fixing atmospheric carbon dioxide as part of the photosynthetic process. However, not all atmospheric carbon is in the form of the ^{12}C isotope. Around 1% is ^{13}C. Rubisco evolved to handle the almost universal ^{12}C and so discriminates against ^{13}C, leaving it behind in the atmosphere. If photosynthetic activity increases (as it does each summer in each hemisphere) then the increase in atmospheric ^{13}C left behind can be measured. This also works if photosynthesis increases due to global warming, because in a warmer world the thermal growing season (TGS) is longer. On the other hand, isotopes of ^{12}C and ^{13}C dissolve more or less equally well in sea water: in fact, if anything ^{13}C dissolves slightly more easily. Consequently if we can detect changes in atmospheric ^{13}C above and beyond the seasonal changes in a hemisphere that we would expect, we can see whether the photosynthetic pump is working harder or not. Similarly, carbonic anhydrase works on the ^{16}O isotope of oxygen and discriminates against ^{18}O. Isotopic studies are therefore an increasingly important tool in understanding how the carbon cycle works.

Ascertaining the carbon cycle's details is the subject of considerable on-going research. In terms of addressing the problem of increasing atmospheric carbon dioxide, the solutions will almost inevitably involve modifying carbon flows between reservoirs such that the atmosphere's carbon burden will be reduced. We will return to this towards the end of this section. Before doing so it is important to note that this on-going carbon-cycle research does not just provide extra detail but still turns up major surprises.

One such recent (2006) surprise was the possibility that plants in aerobic conditions (with oxygen available) produce methane (Keppler *et al.*, 2006). Indeed it was so surprising that *Nature* ran a small article in its news section entitled 'How could we have missed this?' The discovery was almost fortuitous in that it had been thought that all the principal sources of atmospheric methane had been identified even if their individual quantification needed to be refined. To ensure that it was methane from plants (and not microbes) the researchers attempted to kill off bacteria on the plants with radiation. They also removed methane from the air in the incubators in which the plants were to be grown. Although the amounts of methane detected from individual plants were small, globally it amounted to a significant source. The researchers who made the discovery could only make a very rough estimate (as work has yet to be done on an appropriately representative range of species and conditions) but they thought that the annual atmospheric contribution could be between 60–240 million t (Keppler *et al.*, 2006). This is between one-twelfth and one-third of the annual amount entering the atmosphere.

As for the year-on-year growth in atmospheric carbon dioxide since the beginning of the Industrial Revolution (as stated above) this has been carefully charted. It has been done so in two main ways. First, in recent times (since the middle of the twentieth century) there has been direct measurement of atmospheric carbon dioxide. Second, there has been historic measurement from bubbles of air trapped in ice caps (mainly from either Greenland or Antarctica)

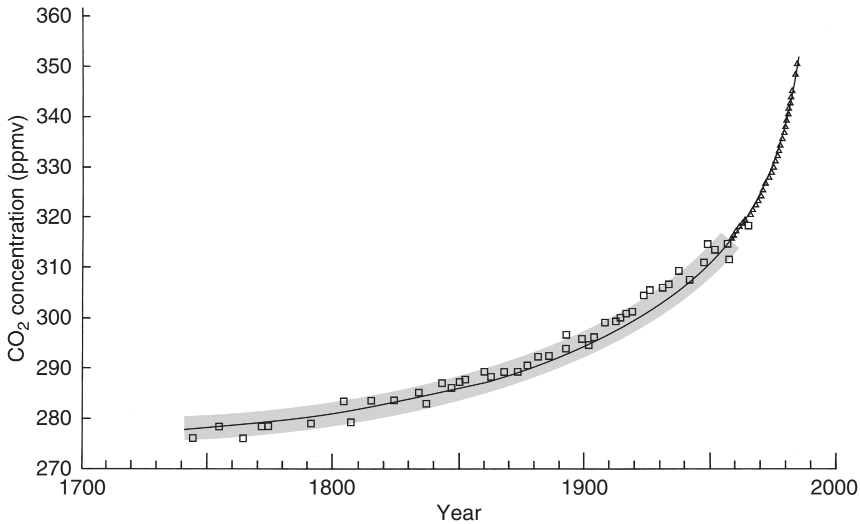

Figure 1.5 The annual growth in atmospheric carbon dioxide. □, Measurements on air trapped in ice from Antarctica; △, direct measurements taken in Hawaii.

as snow fell and then the snow turned to ice. Together these show a continuous growth in the atmospheric concentration from around the time of the Industrial Revolution through to the present (see Figure 1.5).

Much (but, remember, not all) of this growth in atmospheric carbon dioxide is due to the burning of fossil fuels. In essence this represents a short-circuiting of the aforementioned deep carbon cycle: the part of the carbon cycle that takes millions of years to complete. For while, as discussed above, much of the annual movement of carbon dioxide is due to respiratory and photosynthetic processes and contributes to the fast carbon cycle, there is also a slower accumulation of about 1 billion t of carbon a year in marine sediments and more being trapped terrestrially in soils and wetlands. After millions of years much of this ultimately ends up as coal and oil, the larger deposits of which we have only recently (in geological terms) mined and burned as fossil fuels. We are burning these fossil fuels at a far faster rate, thousands of times faster, than they are currently being formed, for the process of fossil fuel formation continues today. It is as if there are two carbon cycles within the overall carbon cycle. One is driven by photosynthesis, respiration and forest fires and operates over a short period of time. The other is the deep carbon cycle operating in so-called deep time of many millions of years and is driven by the geological formation and entrapment of fossil fuels and the tectonic subduction of carbon-rich sediments at the edge of some plates followed by the emission of carbon from volcanoes.

There is currently much research being done to elucidate the carbon cycle's operation, and to measure or infer carbon sinks (Houghton, 2002). This work might be grouped as follows.

1. Global budgets based on atmospheric data and models. The use of data from nearly 100 sites around the Earth of atmospheric carbon dioxide and isotopes.
2. Global budgets based on models of oceanic carbon uptake. The use of models of the oceans' carbon cycle and chemistry linked to those of terrestrial and atmospheric sources.
3. Regional carbon budgets from forest inventories. Many developed nations have national forest inventories and changes in volumes over time can indicate sources or sinks of carbon. However, we are a long way from making this accurate, either on a national basis or for global coverage, although progress is being made.
4. Direct measurements of carbon dioxide above ecosystems. Using stand towers in forests it is possible to measure changes in carbon dioxide being given off or absorbed. (This is quite different from measuring atmospheric carbon dioxide on top of a Hawaiian volcano (one of the key measurement sites) combined with scores of other direct atmospheric measurements to obtain a hemispheric average.)
5. Earth-system science modelling using ecosystem physiology. Using global models built up from global biome and ecosystem data. One of the big questions here (apart from the accuracy of the size of the ecosystem components) is whether all the important ecosystem processes have been included or properly quantified.
6. Carbon models based on changes in land use. This is related to item 5 and has similar constraints.

Having looked at the broad areas of research into the carbon cycle, this leads us on to the question of whether, because we are already altering one part of the carbon cycle so as to increase atmospheric carbon dioxide, we can alter another part to counteract this effect? Given that carbon dioxide is the principal anthropogenic greenhouse gas, and that the carbon cycle is the determining phenomenon in its atmospheric concentration, it would at least appear logical that we might alter the way carbon is currently cycled so as to offset atmospheric carbon increases. One way would be to increase terrestrial photosynthesis through planting new forests, so sequestering carbon, and we will return to forests and biofuel options later (see the end of Chapter 7). Another might be to increase marine photosynthesis.

Marine photosynthesis is mainly carried out by phytoplankton in the open oceans. Here the dominant species are principally the prokaryotes (organisms without internal structures surrounded by cell membranes) *Prochlorococcus* and *Synechococcus*. Both are cyanobacteria (also known as blue-green algae). In terms of crude numbers, *Prochlorococcus* is probably the most populous species on the planet. In addition to sunlight, carbon dioxide and water, these plankton species also require nitrates, phosphates and small amounts of metals. In the ocean, close to the surface, more than enough sunlight is present to drive photosynthesis, but it has been found (in parts of the Pacific at least) that raising the concentration of iron to about 4 nM (nano moles per litre) results in planktonic blooms and associated increased photosynthetic production. The most dramatic of these experiments have been the IronEx I (1993) and II (1996) experiments that covered an area of about 70 km^2, although an area larger than this (1000 km^2) had to be surveyed due to the blooms' drift. This has led to the speculation that it may be possible to use oceanic iron fertilisation to sequester atmospheric carbon. However, modifying the base of some of the planet's major ecosystems, such as in this way, may well carry with it unacceptable ecological risks. Furthermore, it is one thing for winds to carry a global load of minerals to fertilise the oceans and quite another for humans to do so. Indeed, it appears that the energy required to distribute the iron over the ocean surface would roughly equate in fossil-fuel terms with the carbon assimilated. Even so, it does appear that in the past natural changes in the carbon cycle, almost certainly involving the marine component, have had a major effect on the global climate (Coale *et al*., 1996).

1.4 Natural changes in the carbon cycle

We know that atmospheric carbon dioxide plays a major role in contributing to the natural greenhouse effect and we also know that this natural greenhouse effect has varied in strength in the past. Perhaps the most pronounced evidence comes from Antarctic ice cores. Snow falls in Antarctica to form ice and in the process tiny bubbles of air from the atmosphere become trapped and sealed within it. As more snow falls, more ice with bubbles builds up. By drilling a core into the ice it is possible to retrieve atmospheric samples of times past. Indeed, cores at one spot, Vostok in eastern Antarctica, have provided an atmospheric record going back well over 100 000 years. This is a long-enough time to cover the last glacial–interglacial cycle (and more; a glacial being the cool part of the current ice age compared with the warmer interglacials, such as the one we are presently in; see Chapter 3). The ice at Vostok is well over 2 km thick and the cores retrieved in the mid-1980s through to the present have clearly showed that concentrations of carbon dioxide and methane were far lower during the cool glacials than they were during the warmer interglacials. These palaeo-concentrations can be directly compared to the estimated

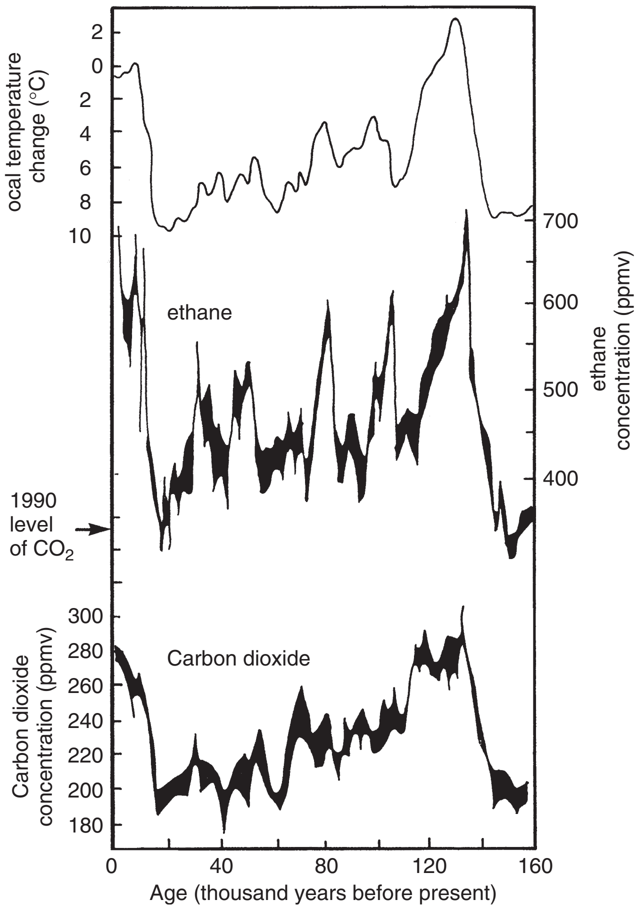

Figure 1.6 Atmospheric carbon dioxide and methane palaeo-record for the past glacial–interglacial cycle plotted with regional temperature change as indicated by the ice hydrogen isotope proxy. Adapted from Barnola *et al.* (1987) and Chappelaz *et al.* (1990), reproduced from the IPCC (1990) with permission.

difference – from the ice-water's deuterium concentration – in temperature between the oceans from which water at that time evaporated and when it fell as snow. This is because it takes more energy (heat) to evaporate water containing the heavier deuterium isotope of hydrogen (^{2}H) than water made up of the common isotope of hydrogen (^{1}H). Therefore, a plot of the ice-core's deuterium concentration gives an indication of regional temperature. Such temperature changes, it can be seen, closely correlate with carbon dioxide and methane concentrations (see Figure 1.6). Such ice-core evidence suggests that atmospheric carbon – be it carbon dioxide or methane – really is linked to climate. Because we know from laboratory analysis that these gases are greenhouse gases (absorbing long-wave infrared radiation), we can deduce that this is the mechanism linking them to climate. Equally importantly, because we know that the atmospheric concentrations of both these gases are affected, if not determined, by the carbon cycle, we have a direct link between the carbon cycle and climate. As one of the carbon cycle's key drivers is photosynthesis, we can see that life is clearly linked to the global climate.

1.5 Pacemaker of the glacial–interglacial cycles

There have been a score or so of these glacial–interglacial cycles over the past 2 million years and, at first sight, these have an apparent regularity. The question then arises as to whether there is anything causal driving this periodicity.

In the 1920s the Serbian mathematician Milutin Milankovitch (although owing a debt to the work of James Croll in 1864) suggested that minute variations in the Earth's orbit could affect the sunlight reaching its surface. This happens largely because the Earth's geography is currently asymmetric: at the present moment in geological time the northern hemisphere is largely land-dominated while the southern is ocean-dominated, so each hemisphere differs in the way it absorbs the Sun's heat. Also at the present time the positioning (through plate tectonics) of the North and South American and the Afro-Eurasian continents restricts oceanic currents, and hence heat transport, about the planet. Oceanic currents are further restricted at the poles, in the north by the North American and Asian continents and in the south by Antarctica. The way heat is accepted by and transported about the Earth under these constraints makes the planet prone to glacials. Milankovitch calculated a theoretical energy curve for changes over time based on the variations of three orbital parameters: angle of axial tilt, or obliquity, which varies between 22° and 24.6° over a 41 000-year cycle; orbital eccentricity (the degree of elliptical deviation from a true circle), which varies every 93 000–136 000 years (so, approximately 100 000 years) between a true circle (an eccentricity of 0) and an ellipse (of eccentricity 0.05) and back again (there is also a 400 000-year resonance); and precession of the equinoxes (the way the Earth's axis spins slowly like a gyroscope), which takes place with a cycle of roughly 19 000–23 000 years (effectively 22 000 years; see Figure 1.7). The climatic relevance of this last, put simply, means that at a specific time of year, say mid summer's day, the Earth is closer or not to the Sun than on other mid summer days. Pulling all these factors together Milankovitch could predict when the Earth was likely to experience a cool glacial or a warm interglacial (Milankovitch, 1920).

Milankovitch concluded that a drop in the amount of sunlight falling on the northern hemisphere at the end of both the precession and tilt cycles would make it more likely for there to be a glacial and that when the opposite happened it would coincide with the timing of an interglacial. For many years Milankovitch's theory did not have much currency. This was due to

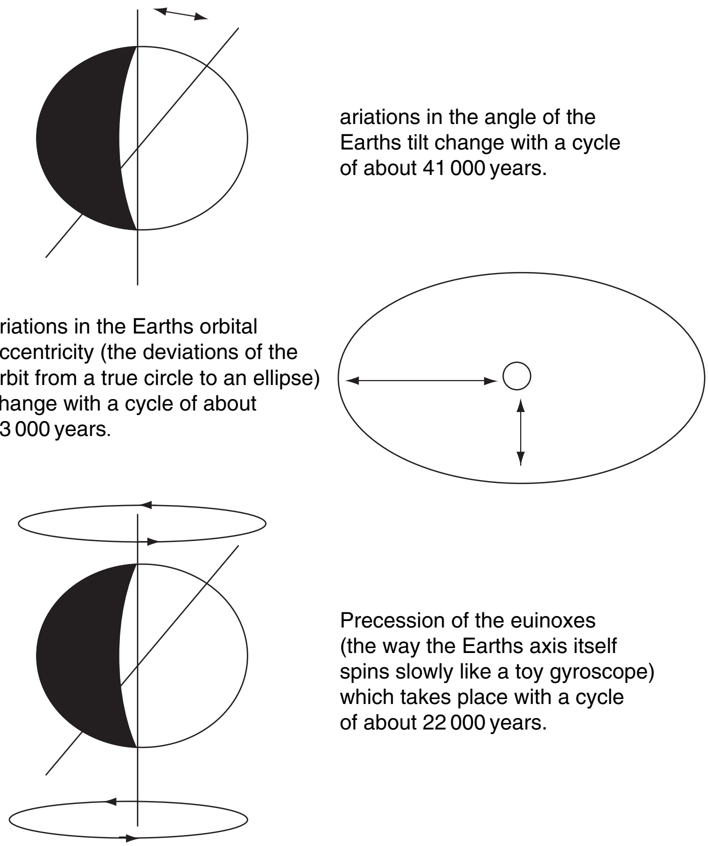

Figure 1.7 Milankovitch orbital parameters of eccentricity, axial tilt and precession of the equinoxes. Each parameter varies through a cycle of different period. Each affects the way the Earth is warmed by the Sun.

two main things. First, for much of this time there was no real understanding of when in the past glacials and interglacials had actually taken place, so Milankovitch's theory could not be checked. Second, the variations in the solar energy falling on a square metre in the northern hemisphere that Milankovitch was talking about were of the order of $0.7\,\mathrm{W\,m^{-2}}$; in other words less than one-tenth of 1% of the sunlight (solar constant being $1400\,\mathrm{W\,m^{-2}}$) bathing the planet. What turned things around was related to the palaeo-evidence from Antarctica's ice cores in the 1970s and 1980s of when glacials and interglacials had taken place. This confirmed Milankovitch's timings and, as we shall see below, there is a considerable body of other biotic evidence corroborating the timing of past climates and climatic change.

If Milankovitch's theory simply provides a glacial–interglacial pacemaker but does not account for sufficient energy changes needed to instigate and terminate glacials, then what is amplifying this signal? The answer lies within the complexity of the global bio-geosphere system (from here on simply referred to as the biosphere system). There are numerous factors determining the global climate. Some, such as silicate erosion (see Chapter 3), affect the planet over long timescales. Others, such as the burning of fossil fuels (a major factor), stratospheric and tropospheric ozone (medium factors) and biomass burning, mineral-dust aerosols and variations in the Sun's energy output (very low factors), affect the climate on timescales of far less than a century. Other factors we still know little about and so their climatic effects are hard to quantify (such as aircraft con (condensation) trails; see Chapter 5). Complicating matters further still, there are many factors that conspire, or interact synergistically, to affect the climate with positive or negative feedback. These feedbacks either amplify climate change or have a stabilising effect. This text focuses on the biology of climate change but it is important for life scientists interested in climate change to have at least a basic appreciation that such feedbacks exist. Figure 1.8 illustrates three such feedbacks (there are many). Figure 1.8a and 1.8b are physical systems and might operate on a lifeless planet. These are both examples of positive feedback that add to, reinforce or amplify any forcing of the climate. That is to say, if something (be it a release of a greenhouse gas, either human-made or natural) forces the climate to warm up, then these feedbacks will serve to amplify the net warming.

Figure 1.8c represents a biophysical feedback system of a different kind. This is an example of a negative-feedback system that dampens any net change in the climate. We have already referred to iron that can fertilise the oceans, so encouraging algae that in turn draws down carbon dioxide from the atmosphere, so reducing the greenhouse effect and cooling the planet. Take this a step further. Consider a world slightly warmer than ours. Being slightly warmer there is more evaporation from the oceans; more evaporation means more rainfall (and/or snow), which in turn means more erosion. This increased geological erosion increases the amounts of iron (eroded from minerals) transported to the oceans that in turn encourages algae, which draws down atmospheric carbon dioxide. Of course, the timescale and magnitude of this natural effect may not be as large as some might wish, hence the discussion as to whether we should deliberately fertilise oceans with iron or take some other measure (although it would be unwise to tinker with the planet's biosphere mechanisms without a thorough understanding). Given that there are feedback processes that amplify change as well as those that stabilise the climate, it is not surprising that changes in the global climate are not always gentle. For example, we do not see a gentle segue from a glacial to an interglacial. Instead we see a sharp transition between the two (see Figure 1.6). It is as if positive feedback encourages sharp changes while negative feedback encourages stable

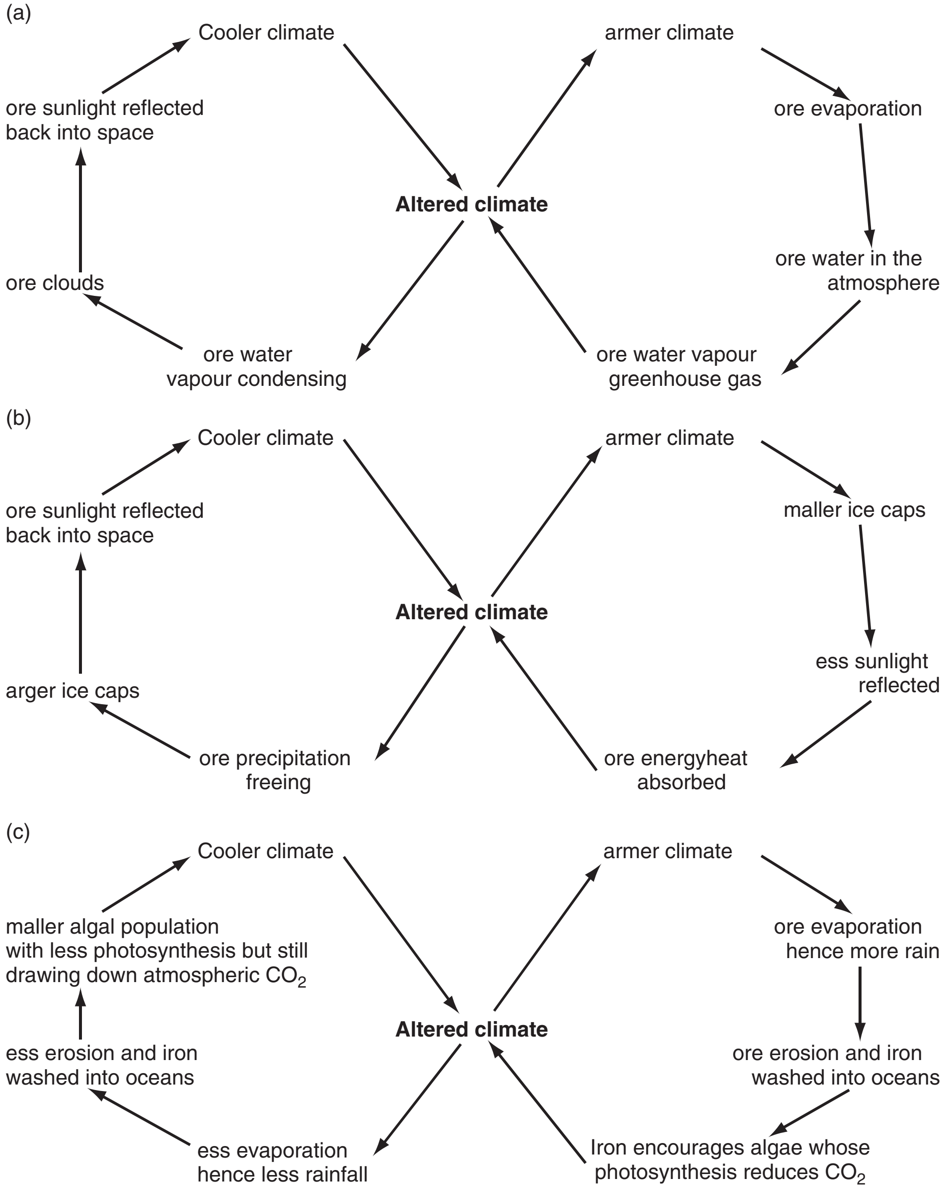

Figure 1.8 Examples of interacting positive- and negative-feedback mechanisms affecting climate change.

states and that either one or other of these two types of feedback dominates at any given time. The combined global climate picture is one of stable (or semi-stable) states between which there is occasional rapid flipping. Here one of the main pacemakers timing these flips is the combination of Milankovitch's orbital parameters.

The question that arises from all of this is whether, with current global warming, the Earth is now shifting towards a new feedback system that may encourage further warming? One example of such a concern is that of carbon in soils, especially at high latitudes, and whether it may be released through warming into the atmosphere. Such soils include peatlands that are at such a high latitude that they are either frozen for part of the year or are permafrosts. Michelle Mack from the University of Florida and colleagues (Mack *et al.*, 2004), including those from the University of Alaska Fairbanks, have looked at carbon storage in Alaskan tundra. Such carbon storage in tundra and boreal soils is thought to be constrained by carbon–nutrient interactions because plant matter is the source of much (nearly all) soil carbon and plant growth is usually nitrogen-limited. Should soils warm in response to climate change, it is thought that nutrient mineralisation from soil organic matter will increase. This should increase plant growth. However, total-ecosystem carbon storage will depend on the balance between plant growth (primary productivity) and decomposition. Experiments at lower latitudes (in temperate and tropical zones) have given variable results (although we will cite a major (albeit rough) assessment of European soil carbon in Chapter 7), but high-latitude ecosystems, because of the large amount of carbon in their soil, show a clearer relationship between productivity and soil carbon storage. In 1981 Mack and colleagues began one of the longest-running nutrient-addition experiments in Alaska by adding 10 g of nitrogen and 5 g of phosphorus m^{-2} $year^{-1}$. This is about five to eight times the natural deposition rate in moist acidic tundra soils. Two decades later and poaceden or the graminoid (grass) tundra – which is dominated by the tussock-forming sheathed cottonsedge (*Eriophorum vaginatum*) – had changed to a shrub tundra dominated by the dwarf birch (*Betula nana*). The carbon above ground (in the form of plants and litter) had increased substantially; however, this was more than offset by a decrease in carbon below ground in the soil. This decrease in below-ground carbon was so great that the net result for the ecosystem was a loss of 2000 g of carbon m^{-2} over 20 years. (The ecosystem's nitrogen did not change nearly so much, other than that a greater proportion of it at the end of the experiment was found above ground in the vegetation.) This loss of carbon is approximately 10% of the initial carbon in the ecosystem. The fear is that as globally soils hold 1500 GtC (compared with some 750 GtC in the atmosphere) and that as about a third of soil carbon is in arctic and boreal soils, that warming of these soils might make a significant contribution to atmospheric carbon. This carbon contribution would, should it occur, be beyond what is being added to the atmosphere through human actions such as fossil-fuel burning and land-use change. It would therefore exacerbate current global warming.

Returning to the aforementioned variable results of carbon-release change with temperature in temperate and tropical soils, it is beginning to look as if considering soil carbon to be in various forms with different turnover rates may explain matters. A three carbon-pool model, with each pool having differing turnover times, was proposed in 2005 (Knorr *et al.*, 2005). This was then applied to data from 13 previously published soil-warming experiments covering tropical and temperate soils that lasted over 100 days up to nearly 2 years. It gave somewhat varying results, but importantly this model was compatible with earlier work. What appears to be happening is that the faster-turnover pools of carbon mask the effect of pools with slower and larger turnover. This model also suggests that higher carbon release from warmed soils might continue over a number of decades. This last has yet to be tested, but we may get the chance to find out as the Earth continues to warm up.

To put the Alaskan experiment into context of current increases in atmospheric carbon dioxide and existing carbon pools, high-latitude warming could at some stage further increase the current rate of (largely fossil-fuel-driven) increase in atmospheric carbon dioxide by between half as much again and double, for a period of two decades or more. However, the exact global effect of climate change on soil carbon is uncertain. Nonetheless, the key point here is that warming would itself enable the release of more tundra soil carbon, which would fuel further warming, and so on. (This is another positive-feedback cycle.) The three-pool carbon soil model, applied to real experimental results, suggests that increases in soil carbon release with temperature rises also apply to temperate and tropical soils and not just to high-latitude (and high-carbon) boreal soils. As we shall see (Chapter 7), this could undermine the policy proposals of temperate nations to use soils as carbon sinks as a way of offsetting atmospheric carbon dioxide increases from fossil-fuel burning, but for now it is worth noting that soil carbon has a feedback to atmospheric carbon dioxide mediated by temperature change even if the precise strengths of this feedback have yet to be discerned.

So much for the broad picture of interacting feedback cycles and flips between semi-stable states. Not surprisingly, climatologists continually monitor research into these positive- and negative-feedback systems. Indeed, climate-modelling research has received multi-million pound investments in recent years, especially since the mid 1980s, when computer technology became sufficiently sophisticated to accommodate models of adequate complexity to provide tolerably useful (or at least interesting) output. The models are good in that they do broadly reflect the global climate, but they (currently) lack detail, both spatially and thermally, and there have been problems with some outputs that simply do not tie up with what we know (see Chapter 5). For example, in the 1990s global models were not particularly good at portraying climates at high latitudes (which are warming far faster than models predict), while the models of the early twenty-first century are including more developed biological components but still have a long way to go. However, the models are continually getting better as they are built with greater resolution (both vertically and horizontally) and incorporate more of the features and processes operating on Earth. Indeed, from the late 1990s onward, programmers turned their attention to including biological processes in their models, so continuing the trend of being able to increasingly match model outputs with expectations based on reality. Here biologists and geologists have much to contribute. For what has taken place climatically is frequently recorded biologically and preserved geologically. Not only do different species live under different climatic regimens but species are affected by climate and these influences can be laid down in ways that are long-lasting (for example, tree rings, to which we will return in Chapter 2).

Prior to the 1980s we had such a poor understanding of the way that the global climate operates that there was great uncertainty as to whether the Earth was warming or cooling. Indeed, when the first ice cores were analysed in the 1970s it was realised that the last glacial had lasted for roughly 100 000 years, whereas the previous interglacial was just 10 000 years. Furthermore, the change between the two was a sudden one and not gradual. Consequently, in the 1970s, given that our current (Holocene) interglacial has already lasted about 10 000 years, there was for a while a genuine concern that a new glacial was imminent and that this global cooling might even threaten civilisation. More research was required into the strengths of the various factors influencing (forcing) climate. It was realised in the 1980s that on balance the factors were warming our planet. Factors such as the current human generation of greenhouse gases were adding to natural warming processes and so were greater than the various cooling factors. The question that remained was how great a warming could we expect from our fossil-fuel generation of carbon dioxide and how would this compare against the current range of other climatic factors? This was the subject of the first IPCC report published in 1990.

1.6 Non-greenhouse influences on climate

Milankovitch variation and the changing sunlight-reflecting (albedo) properties of ice caps (and indeed the solar-reflecting differences of any surface) demonstrate that non-greenhouse considerations do play a part in climate change. They can, through feedback cycles, either increase or decrease the magnitude of change. They can also superimpose their own variability imprint on climate.

However, it is now accepted by nearly all within the climate community that the anthropogenic addition of greenhouse gases is the key factor determining current global warming. But this does not mean that these other, non-greenhouse, factors are not taking place and have no effect on climate.

One such factor has in particular caused some controversy, although it is generally accepted to have a minor effect compared to current anthropogenic climate change. This is the variation in solar output, or changes in the Sun's intensity and has had a major part to play over the three or so billion years of evolution of the Earth's biosphere. As we shall see in Chapter 3, the Sun, being a main-sequence star, is growing significantly warmer over a scale of hundreds of million to billions of years. This has considerable implications when it comes to elucidating the evolution of the biosphere. However, on shorter timescales of hundreds or thousands of years it is comparatively (but not entirely) stable. On even shorter timescales the 11-year sunspot cycle has an impact. But this last effect is small, causing a variation in irradiance of only 0.08%, which is too small to have much effect: changes here may affect the global climate by 0.02–0.4 °C. Changes in sunspot activity do seem to tie in with similar patterns of change in global temperature, but these are superimposed on larger climate changes determined by other factors (Foukal *et al.*, 2004).

The question as to whether the Sun is largely responsible for current global warming came about because the Sun has became slightly more active during the twentieth century. During much of this time the Earth's temperature rose and fell almost simultaneously with changes in solar activity. There is also the question of the so-called Little Ice Age and solar activity, and we will return to this in Chapters 4 and 5.

Since 1978 we have been able to take space-borne measurements of solar output and correlate them with sunspot activity, for which we have previously only had an observational record going back a few centuries. The relationship is not clear but there *is* a relationship. However, there is also another larger, longer-term (over a timescale of centuries) solar component whose exact historic magnitude is speculative, but roughly five times that of the solar variation reflected by sunspot activity. Furthermore, there does seem to be a correlation between global temperature and solar output (as we shall see in Chapter 4, which might account for the Little Ice Age) but is this relationship real, partial, or just a coincidence?

In 2004 a team of five European researchers from Germany, Finland and Switzerland used the carbon isotope ^{14}C from tree rings going back 11 000 years (Solanki *et al.*, 2004). It is usual to think of ^{14}C as a means of dating objects using radioactivity as ^{14}C is produced in the upper atmosphere at *roughly* a constant rate. ^{14}C is then absorbed into living things and begins to slowly decay at a known exponential rate. So the amount of ^{14}C left compared to the stable ^{12}C enables one to date objects, albeit with a certain amount of error. Yet ^{14}C is not produced at an *exactly* constant rate. ^{14}C is produced in the upper atmosphere due to the action of cosmic rays from the Sun on nitrogen and carbon atoms; the level of cosmic rays is an indication of the Sun's output. Counting tree rings from overlapping samples of wood enables each ring to be dated in a different, more accurate, way to carbon dating. It is therefore possible to deduce whether at any one time more or less ^{14}C was produced compared to what would have been produced if solar activity was constant. The research team's ^{14}C-determined calculation of solar output was corroborated by ^{10}Be (a beryllium isotope) from Antarctic and Greenland ice cores, as this isotope also relates to solar output. The researchers found that there was indeed unusually high solar activity at the end of the twentieth century and that this would have certainly contributed to some of the global warming experienced then. However, it could not account for it all and was 'unlikely to be the prime cause' (Solanki *et al*., 2004).

What seems to be happening is this. There are many factors affecting the climate. Some 'force' it in a positive (warming) way and others in a negative way. Furthermore, some are strong climate forcers and some weak. Greenhouse gases are strong climate-forcing factors. Variations in the Sun's output over tens of thousands of years do occur but are comparatively small. Their effects may be superimposed on the climate change that is determined by the sum total of all other forcing agents and as such they may account for small changes in the climate (and possibly even the Little Ice Age). However, it is difficult for small climate forcing (such as the small increase in twentieth-century solar output) to account for the large temperature changes measured. Remember, the Milankovitch variations in energy reaching the northern hemisphere in the summer are small. As we shall see in Chapters 3 and 4, these small changes in solar radiation help trigger larger changes in carbon dioxide and methane greenhouse gases as the Earth moves between (glacial–interglacial) climate modes. One should not be surprised that greenhouse gases are not the only positive climate-forcing factors contributing to current warming. There are others (both positive and negative), and increases in solar output are but one. These others include volcanic activity, marine release of methane and (with regional effects on climate) oceanic and atmospheric circulation. We shall return to these later in the book. While these other factors can play an important part in some climate change, they are not the dominant factors of current global warming. Even so, they cannot be easily dismissed because, as we shall see, these factors could make a serious contribution to climate change in the future and in particular circulation changes can help flip climate regimens between semi-stable states.

1.7 The water cycle, climate change and biology

As something noted above, and to which we will occasionally return later in this book, one of the things one would reasonably expect in a warmer world is more evaporation from the ocean. Again, as previously noted, this expectation is at least in part corroborated by computer models of atmospheric water vapour: so, global warming affects the water cycle. This leads us to another expectation that we would reasonably anticipate from more evaporation, that there would be more precipitation (rain and snow) and so in turn also increased river flow. But how reasonable are these expectations?

The Earth's climatic system is complex. Furthermore, biology is not just affected by a changing climate; biology, as we shall see, itself plays a key part in affecting the nature of climate change itself and in affecting some of the consequences of that change. Having said this, not all these complications are biological. Nonetheless, these complexities need to be taken into account.

First of all, although a warmer world will lead to more evaporation (other factors, such as the complete solar spectrum, remaining constant), more evaporation does not in itself necessarily mean more precipitation. To take an extreme example, Venus is a far warmer planet than the Earth and its atmosphere imparts a far more powerful greenhouse effect. Indeed, Venus is so warm that water exists solely in the form of water vapour. There is no rain to soak the ground on Venus and there are no oceans. Second, although a warmer world results in more ocean evaporation, if, hypothetically speaking, part of this extra water vapour does return as a partial increase in precipitation this does not mean that river flow would necessarily increase. It could be, hypothetically, that the increased evaporation means that the excess precipitation evaporates before it reaches the rivers (we shall return to this later). Alternatively, it may be that rainfall would increase mainly over the oceans, so leaving river flow unaffected. Third, other factors and indeed biological processes may well play their part. So it is important to identify these factors (or as many as possible) and to try to quantify them.

Time for a quick reality check. First, as already noted, the global climate is an average made up of regional and annual variation. With a changing global climate not only will some climatic components change in some places, and at some times more than others, but it is possible that in some places (and/or times) there may be a change in the opposite direction to the overall trend. (This has been seized on by some, especially in the 1990s, to argue that global warming is not taking place. Such arguments are based on selective and atypical data, with the fallacious claim that the data is typical.) Second, there are other non-greenhouse-gas factors operating. Temperature is not the sole mechanism behind evaporation; direct sunlight (electromagnetic radiation of appropriate frequency) also plays a part. A photon of sunlight can excite a water molecule causing it to leave its liquid-state companions and become vapour. As we shall see later in this chapter changes in the amount of sunlight reaching the Earth's surface have been happening and have resulted in so-called global dimming due to pollution particles. Another factor affecting water becoming water vapour is biology.

The routes from liquid water back to water vapour are not restricted to straightforward evaporation but also plant transpiration as part of photosynthesis in terrestrial plants. For this reason evapotranspiration (the total water loss from an area through evaporation and vegetation transpiration) is important. Now let us return from theory to reality.

A warmer world due to increased greenhouse gases will, among other things, affect plant physiology. Plants exchange gas and water with the atmosphere through openings on the surface of leaves called stomata. Stomata open and close to regulate photosynthesis in the short term. (Also, as we shall shortly see, in the longer term, stomatal densities have been shown to vary on more geological timescales with atmospheric carbon dioxide concentrations – see Chapter 2.) In a warmer, more carbon dioxide-rich world with higher rainfall that serves to enhance photosynthesis, all other things being equal, we might expect plant homoeostatic processes (physiological mechanisms acting to keep functions stable) to dampen photosynthesis. If this were happening then we would reasonably expect plant transpiration to decrease. This in turn would lower a plant-covered water catchment's evapotranspiration and so more water would remain in the ground to percolate through to streams. River flow would increase. So much for theoretical expectations. The question then becomes one of how do the various factors of changed precipitation, warmth, plant physiology and river flow interact?

Here it is possible to model the individual processes. We do have climate records of temperature and precipitation covering many decades, measurements of solar radiation reaching the surface, as well as those of river flow. We also know about plant physiology and so can apply broad parameters to plant physiology over a region as well as factors such as deforestation and land use. In short, we know both actual river flow for principal catchments on each of the continents and, broadly, how the various factors that contribute to river flow have changed over the last century. A model of twentieth-century continental water runoff has been constructed that reflects actual river-flow measurements. It is then possible to examine the model conducting a 'sensitivity analysis' (or 'optimal fingerprinting' or 'detection and attribution', the nomenclature varies with research groups) to vary just one factor at a time and to see using statistics how this causes the predicted runoff to differ from reality. It is known that twentieth-century climate change alone is insufficient to account for runoff changes. However, such an analysis of a surface runoff model has indicated that including the suppression of carbon dioxide-induced stomatal closure makes the model's outcome consistent with actual runoff data (Gedney *et al.*, 2006; Matthews, 2006). In short, biology plays a key part in controlling the water cycle to such a degree that without it climate change and other non-biological factors cannot fully explain water-cycle trends.

As we shall see again and again throughout this book, climate and biology are connected: one affects the other and vice versa. Furthermore, humans, as a biological species that also rely on and who are in turn affected by other biological species, are caught in the middle of this climate–biology dynamic. That human action is also a significant driver of current climate change further complicates matters. We need to understand both how our species affects the global climate and the climate–biology dynamic if our growing population is to survive without a decline in either well-being or environmental quality.

1.8 From theory to reality

In the above review of the causes of climate change it can be seen that climate theories, be they that of greenhouse climatic forcing or that of Milankovitch's orbital effects of incoming solar energy, have to be validated. This is done by comparing theory with what actually happens, or has happened, in reality. What is happening can be measured today, although care is needed. For example, satellite remote-sensing devices need proper calibration and we need to know what their data actually mean. (I cite this example because in the 1990s incorrect assumptions were made about some satellite data.) The past 10 years has seen tremendous progress in understanding climate change on two fronts. First, there has been a steady improvement in computer models. This improvement continues but there is still a long way to go, both in terms of reducing uncertainty across the globe and in terms of spatial and temporal resolution (see Chapter 5). These inadequacies mean that even the best models can only present a broad-brush picture of a possible likelihood. The 2001 IPCC report provides some good illustrations of the limitations. For example, it presents (p. 10) two global models of projected changes in precipitation runoff from the 1960s to 2050. Both show decreases in runoff in the Amazon basin, much of the rim of Australia, and Central Europe, and runoff increases in south-east Asia, north-west Canada and southern Alaska. At the moment this does seem to tie in with *some* observations (IPCC, 2001b). This similarity of computer-model output with reality (even though we have yet to reach 2050) is not proof of the various