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.

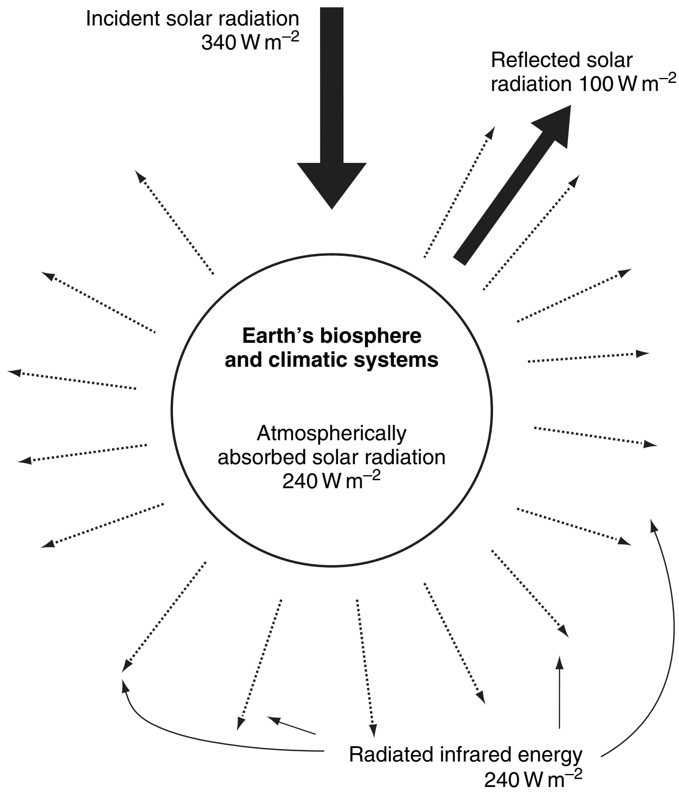

Figure 1.1 A summary of the principal solar-energy flow and balance in the Earth's atmosphere. Not all the high-energy infrared radiation falling on the Earth is reflected back out into space. Some is converted into lower infrared energy in the atmosphere. The result is atmospheric warming. Note: the 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

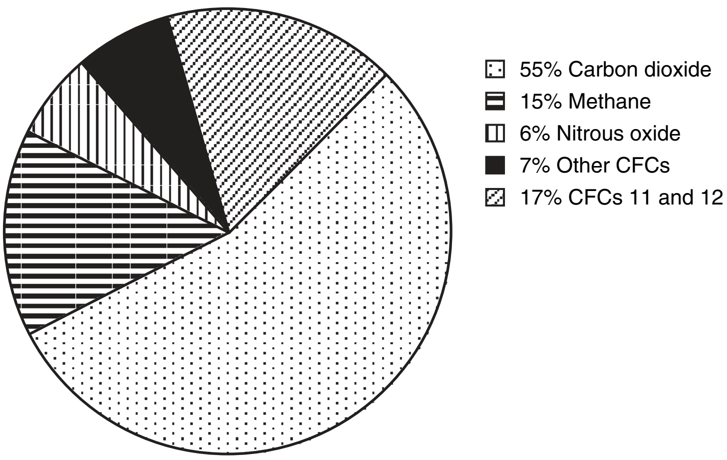

Figure 1.2 The contribution from each of the principal anthropogenic greenhouse gases due to the change in warming (radiative forcing) from 1980 to 1990 (excluding ozone, which may or may not be significant and is difficult to quantify). Data from IPPC (1990).

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