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Jonathan Cowie
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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 UN 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 that 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 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 and atmospheric chemists, for example) 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 refer mainly to specialist journals. Very few libraries in universities or research institutes carry the full range. Fortunately the high-impact-factor and multi-disciplinary journals such as *Science* and *Nature* do publish 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 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

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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 about 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. This 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, which leads to the same concluding picture.

Indeed, because there is so much evidence contributing to the big picture that some may well find that evidence from their own specialist area of work is not included, or is covered only 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

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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 of change. 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 rather than 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. Reviews and comments online are positively welcome, if not encouraged, be they in print, on websites, in blogs or on social networking sites. I do read and note any comments that I find and they all helped with the revision and expansion process for this second edition, and will help with any further work I may undertake.

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1 An introduction to climate change

In most places on this planet's terrestrial surface there are the signs of life. Even in 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 than those found there today. Why? 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 ones with narrow, needle-type leaves) live in one place and not another has to do with climate. Climate has a fundamental influence on 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 because different climatic regimens existed at that place at those times.

It is also possible to turn this truism on its head and use biology to understand the climate. Biological remains are an aspect of past climates (which we will come to in Chapter 2). 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 and 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 understanding climate change is absolutely critical if we are to predict the likely fate of species in a certain region. As mentioned, 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*. 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 which have now gone, primarily because of a change in climate (this will be examined in Chapter 5).

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 altering the global climate in a profound way that also

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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 on 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, which is why it is hard to make 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. An analogy is what physicists and engineers refer to as the signal-to-noise ratio, which applies to electrical currents or an electromagnetic signal, such as 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, by itself one very hot summer (or drought, or heavy monsoon or whatever) 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, whereby an atmosphere serves to warm a planet. These papers almost did not get written because 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 either is 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, 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 it is trapped in the rocks that are 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 that 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, which is estimated to be 6.626×10^{-34} J/s). Therefore, 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 wavelengths, especially lower-energy infrared (heat-level), 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.

$$E = h\mathrm{v}.$$

E (energy) is measured in joules and v (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, although transparent to many higher frequencies, is opaque to many of the lower thermal frequencies. The atmosphere traps these and so warms up. 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

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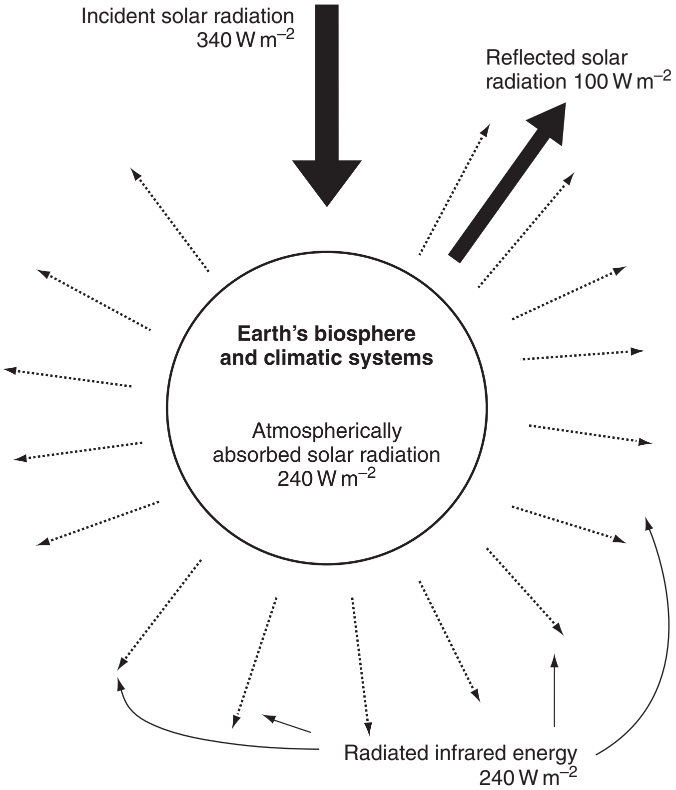

Fig. 1.1 A summary of the principal solar-energy flow and balance in the Earth's atmosphere. Not all the high-energy infrared radiation falling on the Earth is reflected back out into space. Some is converted into lower-energy infrared radiation in the atmosphere. The result is atmospheric warming. Note: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

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 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 talked about most frequently is carbon dioxide (CO_2). Others do not occur naturally. For example, halocarbons such as chlorofluorocarbons (CFCs) 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, such as carbon dioxide, the atmospheric concentrations of which are further enhanced by human action.

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 that 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'.

Fourier, Tyndall and Arrhenius are, today, rightly credited with providing the initial grounding science for greenhouse theory. Yet it is often forgotten that in the few decades following 1896 this theory was not high on many scientists' research agendas, and indeed serious doubts arose as to the importance of the increase in atmospheric carbon dioxide in changing the Earth's global climate. However, in 1938 a steam technologist working for the British Electrical and Allied Industries Research Association, one Guy Stewart Callendar, managed to get a paper published in the *Quarterly Journal of the Royal Meteorological Society* in which he noted that humankind had added some 150 000 tons of carbon dioxide to the Earth's atmosphere and that this, he calculated, would have warmed the atmosphere by some 0.003°C per year. He also looked at (a limited number of) meteorological records that suggested the climate's temperature had increased at an average rate of 0.005°C per year (Callendar refined this last estimate in 1961 using a larger meteorological data set). Callendar's meteorological estimates and greenhouse warming calculation were well within the right order of magnitude and his work, albeit limited, deserves to be remembered in the history of climate change science.

Guy Callendar was not alone. At the end of August 1972 an atmospheric scientist, J. S. Sawyer, estimated that the warming that might be expected with a continued growth in fossil fuel emissions of carbon dioxide to 2000 would be 0.6°C. This was quite prescient because less than half the total amount of carbon dioxide released into the atmosphere between the Industrial Revolution and 2000 was in the atmosphere by 1970. In addition, as we shall see in Chapter 5, the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) consider that there was very roughly 1°C of warming from the beginning of the Industrial Revolution to 1990, so 0.6°C really is not bad for about half the carbon dioxide. What is more, for a couple of decades up to 1970 the global temperature had actually been declining, making Sawyer's prediction particularly brave as it seemingly went against the grain. So he was very close and, with the benefit of hindsight, we can now see that between the 1970s and 2000 the global temperature rose by close to 0.5°C!

Today the atmosphere is indeed changing, as August Arrhenius thought it might, with the concentration of carbon dioxide increasing in recent times, largely due to the burning of fossil fuels. In 1765, prior to the Industrial Revolution, the Earth's atmosphere contained 280 parts per million by volume (ppmv) of carbon dioxide. By 1990 (which is, as we shall see, a key policy date) it contained 354 parts per million (ppm; either by mass or by volume) and was still rising. By 2005 (when this

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Table 1.1 Summary of the principal greenhouse gases (with the exception of tropospheric ozone, O_3, due to a 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
2010	388 ppm	1.809 ppm	240 ppt	533 ppt	323 ppb
Atmospheric lifetime (years)	50–200	12	45	100	114

ppb, parts per billion; ppm, parts per million; ppt, parts per trillion (all by volume).

book's first edition was written) it had topped 380 ppm and by 2011 (when drafting the second edition) it had reached more than 392 ppm and was still climbing.

If this rise is because of the addition of carbon dioxide to the atmosphere (and it is) then it would be useful to get an idea as to how much carbon is needed to raise the concentration by 1 ppm. Well, the Earth's atmosphere weighs around 5.137×10^{18} kg, which means that a rise of 1 ppm of CO_2 equates to 2.13 Gt of carbon (or 7.81 Gt of CO_2 as carbon dioxide is heavier than carbon).[1]

Over the time since the Industrial Revolution 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 (which I will discuss in Chapter 2) as well as some direct measurements, we can deduce that it has taken place. Furthermore, we now know that Tyndall was right. With less greenhouse gas in the atmosphere the Earth cools and there are ice ages (glacials); 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 public 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 IPCC. Its four main reports, or assessments (IPCC, 1990, 1995, 2001a, 2007), 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.

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.

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[1] You may have noticed that some estimates of CO_2 emissions seem to be about three-and-a-half times as large as others. This is because numbers are sometimes expressed as the mass of CO_2 but are in this book mainly expressed in terms of the mass of the carbon (C). Because carbon cycles through the atmosphere, oceans, plants, fuels, etc., and changes the ways in which it is combined with other elements, it is often easier to keep track only of the flows of carbon. Emissions expressed in units of carbon can be easily converted to emissions in CO_2 units by adjusting for the mass of the attached oxygen atoms; that is, by multiplying by the ratios of the molecular weights of carbon dioxide and carbon respectively, 44/12, or 3.67.

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 post-18th-century changes to the concentrations of the various gases, they were attributable to the post-Industrial Revolution anthropogenic 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 have each largely arisen 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. Some of the increase in methane comes from paddy fields, whereas part of the rest comes from the fossil fuel industry and biomass (which includes rotting dead plants and animals, and fermentation in animals). We shall examine this in more detail in the next section when looking at the carbon cycle, but other methane increases (or, in the prehistoric 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 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 that each gas makes, each has different physicochemical properties. These are quantified for each gas in what is called its global warming potential (GWP). GWP is a comparative index for a unit mass of a 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 *must* 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 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. This means that the average life time of a typical molecule will be around 12 years.[2] Conversely, nitrous oxide has an average residence time of more than 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

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[2] Residence times are both estimates and also can alter in different atmospheric conditions such as gas concentration and temperature. So, do not be surprised if you see slightly different figures in the academic literature. Sound advice is to use the most recent as well as authoritative estimates.