

Chapter 2

Global Climate Change

2.1 Introduction

The realisation that increasing concentrations of heat-trapping greenhouse gases like CO₂ would result in rising temperatures is not new. In the 1820s the French scientist Joseph Fourier, building on speculations made a half-century earlier, wondered why the Earth's temperature was higher than it should be, given its distance from the Sun. He hypothesised that this was because the atmosphere was partly opaque to the passage of outgoing infrared radiation. In 1859 the Irish physicist John Tyndall demonstrated experimentally that certain gases in the atmosphere, particularly CO₂ and water vapour, were effective in trapping radiant heat [30]. The Swedish chemist Svante Arrhenius in the early years of the 20th century calculated that a doubling of atmospheric CO₂ concentrations would warm the Earth by about 4°C – a value close to present estimates.

Nevertheless, despite this long history, the topic of global climate change has become a controversial one. Although nearly all climatologists think that continued anthropogenic releases of greenhouse gases at anything like current rates will lead to dangerous change, a small minority dissents. They variously argue instead that any measured temperature increase is mainly the result of changes in solar irradiation, or is caused by natural variability in the complex climate system. Additionally, many popular blog sites do not accept that global warming is real. This uncertainty has been in the past, and in some cases still is, supported by industries and energy-exporting countries who stand to lose financially if controls are placed on CO₂ emissions [29].

Global warming is different from other resource or environmental controversies, such as those concerning nuclear power, or oil depletion. Most governments and international organisations (such as the International Atomic Energy Agency) support the development of nuclear energy, and do not see oil depletion as a constraint on global oil use any time soon, as evidenced by the optimistic forecasts of oil use in 2030 by groups such as the US Energy Information Administration

(EIA) [15]. In contrast, most of the world's governments and international organisations support the scientific consensus on climate change, even if they have great difficulty in translating this support into effective action.

2.2 The Science of Global Warming

Both the academic and popular writings on global warming are now vast. Climatologists Michael MacCracken [24], Michael Mann [25] and Barrie Pittock [35] have provided comprehensive summaries of both the science of global climate change and its likely effects. The report by Allison and others [2], released just before the Copenhagen December 2009 Climate Conference, updates climate findings since the 2007 IPCC report. Here we try to show that the climatologists' concerns about global warming and its consequences are well-founded. We stress in particular the observed changes in the polar regions, not only as an indication of the changes likely in other regions, but because some scientists believe the melting of the Greenland icecap may soon reach the point where it is irreversible.

Nearly all observers now accept that global temperatures have risen over the past century or so. Are we the cause of this observed climate change? Let's start with the obvious: days are warmer than nights, summers are warmer than winters. Why? Clearly, astronomy explains both these facts. The Earth spins on its axis once every 24 hours, and the axis is inclined to the plane of its year-long orbit around the Sun. Climatologists don't argue that all climate change observed in the past was caused by humans. Obviously we humans can't have been the cause of changes that happened before there were any humans. But natural explanations like astronomical changes and plate tectonics can't explain the present ongoing climate changes, as we'll explain in this section.

2.2.1 *The Science Basics*

Every day a huge amount of energy in the form of electromagnetic radiation reaches Earth. About 30 % is immediately reflected by clouds, and by oceans, land and ice – we say that the Earth's albedo is 0.3, Figure 2.1. The other 70 % is absorbed by the land, atmosphere and oceans. So why doesn't planet Earth simply get hotter and hotter, until it melts and finally vaporises away into space? After all, space is a near-vacuum, so very little heat is lost by conduction or convection. That leaves radiation as the only outlet for heat loss. According to the Stefan-Boltzman equation, every body radiates away heat in proportion to the 4th power of its absolute temperature. (Since the absolute zero of temperature occurs at -273°C , values on the absolute temperature scale are simply 273 units higher than the Celsius scale. So 100°C is 373 absolute, or 373 Kelvin (K)). Thus small changes in temperature result in large changes in energy. Just as the Sun loses heat by radiating it away into space, so does the Earth – and the other planets.

Normally, the Earth's surface stays at a constant average annual temperature, because the annual incoming energy from the Sun is roughly balanced by the outgoing radiant energy (expressed as Watts per unit area (W/m^2)). Watts are the units of energy per unit time, also known as power, Joules are the units for energy. Additional factors to consider in this energy balance are the emissivity of the Earth and its atmosphere, the Earth's albedo, and the value of the incoming solar radiation constant (1367 W/m^2) [48].

Emissivity is a measure of the ability of a material to radiate the energy it absorbs. It is a function of the wavelength of the incident radiation and temperature. And, as we discuss below, for the atmosphere, emissivity also depends on composition, the time of day and the presence of clouds. The albedo of the Earth will depend on the surface cover (vegetation, desert, snow *etc.*) of the land and sea, and, like emissivity, on the presence and properties of clouds and aerosols.

Also, despite the balance in the energy flows, there are differences in the properties of the energy being exchanged; we might say that not all energy is equal. When energy from the Sun is exchanged with the Earth, its wavelength changes. The incoming energy is high frequency (visible and ultra-violet) radiation, but the outgoing energy is low frequency (infra-red) radiation. The surface of the Sun is around $5,800 \text{ K}$ [40], whereas the Earth's surface is only about 15°C (288 K). Higher temperature bodies like the Sun have an emission spectrum (the variation of the energy emitted as a function of emission wavelength) with peak emissions occurring at much higher frequencies, and so shorter wavelengths, than low temperature bodies like Earth.

Importantly, the gases which make up the atmosphere respond differently to this radiation. Some atmospheric gases, while transparent to visible radiation, are partly opaque to this out-going infra-red radiation, as Tyndall demonstrated one and a half centuries ago. These gases both absorb this outgoing radiation, and re-emit it (their structure allows the formation of an oscillating electric dipole), with much of this emitted radiation finding its way back to Earth's surface. The chief culprits are water vapour, carbon dioxide, nitrous oxide, methane, ozone, and various halocarbons, including chlorofluorocarbons (CFCs) and similar complex molecules. The chief atmospheric constituents, oxygen and nitrogen and the minor one, argon, remain unaffected. The heating that occurs from this absorption and re-emission process is known as the *greenhouse effect* and the gases responsible, greenhouse gases (GHGs).

The Sun also exerts a variable radiative forcing, and some people see this as the main explanation for the observed temperature rises. Solar irradiance varies over an 11-year cycle with the maximum values being only 0.08% above the minimum ones. The resulting direct forcing is very small, and the measured Earth surface temperature trends show an indiscernible 11-year response of around 0.1°C , as would be expected given the sensitivity in global mean temperature to solar variation [14]. Similarly, reported indirect forcing by increased cosmic ray ionisation of the atmosphere (resulting in changes in cloud properties), does not appear to correspond to measured cloud cover changes. Variations in the solar output are ac-

cordingly considered to be only a minor factor in explaining Earth’s recent temperature rise [41].

Is there any evidence that all this is actually happening in the atmosphere? Chen and colleagues [10] used satellite data to examine the way infrared emissions from Earth have varied from 1970 to 2006. They found that changes in the outgoing longwave radiation spectrum matched those expected from changes in GHG concentrations over the period. Their results provide empirical evidence that increased atmospheric concentrations of greenhouse gases from human activity really are affecting the Earth’s radiation balance.

The end result is that GHGs in the atmosphere prevent some of the back radiation from Earth escaping into space. Since the Earth is then radiating less energy than it receives from the Sun, a continuous net input of energy (or heat) occurs. The result: gradual warming of the Earth’s surface, oceans and atmosphere. Since the Earth is now at a higher temperature, it can radiate away more heat in accordance with the Stefan-Boltzman equation, and move the Earth once more toward thermal equilibrium.

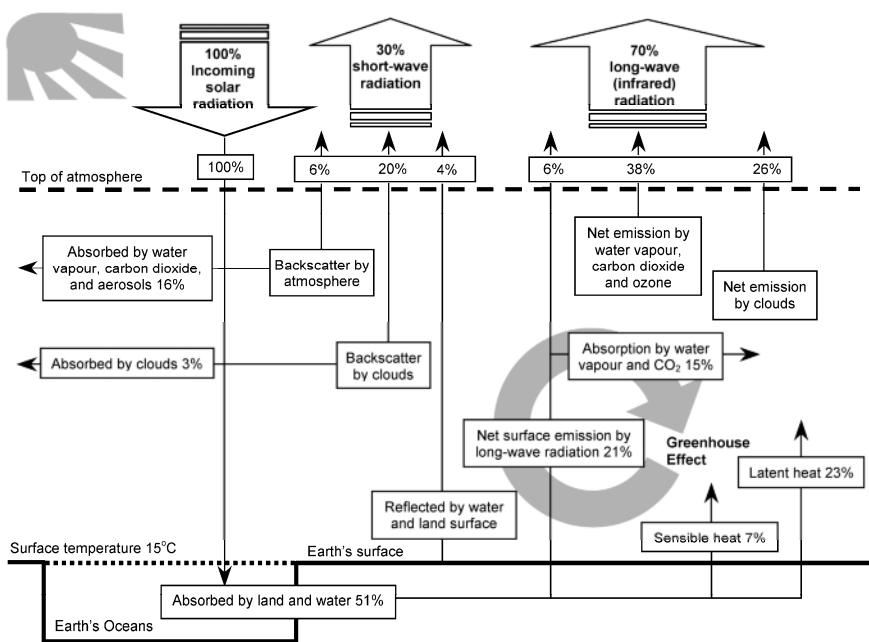


Figure 2.1 Earth’s radiative energy balance and the role of the greenhouse effect. Percentages represent the amount of energy exchanged by a given process. Source: [43]

The greenhouse effect has always been with us, and in fact has made the Earth habitable for humans. The Moon is the same average distance from the Sun as Earth, and so we might expect it to be a similar average annual temperature, but its

measured average temperature is a cold -18°C , compared with the Earth's $+15^{\circ}\text{C}$. The reason for the $+33^{\circ}\text{C}$ difference is that the Earth has a CO_2 -containing atmosphere, but the lighter Moon has lost whatever atmosphere it had. So the Earth's $+15^{\circ}\text{C}$ is often said to be caused by the *natural* greenhouse warming effect, as distinct from the *human* or *enhanced* greenhouse warming effect caused by our cumulative net emissions of GHGs [25].

Other things being equal, then, increasing the volume of heat-trapping gases in the atmosphere, as we have been doing for a century or more, results in warming the Earth's surface. No climate scientist seriously disputes this. The only controversy remaining is about how much dampening of temperature increase will occur from what are termed *negative* feedbacks. Examples are the increased cloud cover that higher temperatures (and thus higher evaporation) will produce, and the draw-down of atmospheric CO_2 from enhanced biomass growth in a CO_2 -rich atmosphere. On the other hand, several *positive* feedbacks also operate, which will result in more global warming than would be expected on the basis of GHG atmospheric concentrations alone. These feedbacks, discussed later in this chapter, include the ice albedo feedback, and methane and CO_2 emissions from melting permafrost.

Since the mid-19th century, average global temperatures have risen by an estimated 0.76°C , most of it in the last few decades [41]. Arctic sea ice is thinning, sea levels are rising, and glaciers in both tropical mountains and temperate lands are retreating. 'The Snows of Kilimanjaro' are disappearing: the Kilimanjaro ice-cap has lost 26% of its area over the period 2000–2007, and now occupies only 15% of its extent found in a 1912 aerial survey. The ice is expected to completely disappear in a few decades, although climate change is not the only cause [42]. Scientists now believe that the temperatures we are presently experiencing are the highest of the last millenium, and, possibly, much longer [41].

2.2.2 *Mathematical Models and the Temperature Record*

We can measure temperatures on land, at various ocean depths, and at various heights in the atmosphere. We can measure the amount of water vapour in the air, the rainfall and its intensity at various locations, and the mass of ice locked up in the world's glaciers. But we also want to know what the climate will be like in the future if we continue to emit CO_2 and other GHGs. Specifically, we need to know what changes in temperature and rainfall will occur and what their distributions will be for given concentrations of GHGs in the atmosphere. One approach used by climate scientists is to construct mathematical models of the energy and material flows in the atmosphere and its interacting systems. Such models are called Global Circulation Models (GCMs) and have been developed from models used to forecast the weather. We discuss the reliability of these models in Chapter 4.

Recently there has been much debate about average global temperatures over the past decade or so, with sceptics claiming falling temperatures. According to

the 2007 IPCC report, except for 1996, the years 1995 to 2006 recorded 11 of the 12 warmest years on record since 1980, with the highest being the strong *el Nino* year of 1998 [41]. More recently, the Met Office Hadley Centre in the UK corrected average surface temperatures for the decade 1999–2008 and did not find any rise – although the values were still high compared to the average for the 20th century. But when short term variability from *el Nino*, solar output variation and volcanic eruptions are allowed for, the measured global temperature changes in recent decades, (including the first decade of the 21st century) are in line with the climatic warming trend of about 0.2 °C per decade predicted by the 2007 IPCC report. Allison and colleagues [2] conclude simply: ‘Every single year of this century (2001–2008) has been among the top ten warmest years since instrumental records began.’ And 2009 is now the fifth warmest year on record.

Nevertheless, climate modelling work shows that decade-long intervals when the temperature is more or less flat should be common, but such periods of no temperature rise should prove rare over intervals of 15 years or more. As the old saying goes: ‘climate is what you expect, weather is what you get.’ Even so, natural variability has its limits [19]. The important point is that given natural variability, we should not base conclusions on short time periods. The higher and longer the rise in average global temperature continues, the more certain we can be that the changes are real. And here lies our dilemma; attaining this certainty comes at some cost, since once we are sure, it may be too late to act.

The data above refer to *average* surface temperature rises, over both land and sea. Actual temperature rises will on average be greater in the high-latitude regions. They will also be greater on land than at the ocean surface, so since oceans cover 70 % of the Earth’s surface, the warming on land will be appreciably higher than the global average. Note that oceans have the capacity to redistribute heat through mixing processes which are unavailable to land masses.

Measuring average surface temperatures and forecasting their future changes is not the only possible metric for assessing global climate change, although it is the one favoured in media discussions of climate change. Roger Pielke [33] argued that a more accurate way of quantifying climate change is to look at how the Earth’s energy balance is changing, as a result of the global imbalance between insolation and out-going thermal radiation. In brief, we should examine how energy, or heat, is steadily accumulating (or decreasing) on the planet. Anderson [4] summarised the results of such calculations for heat flows over the past half-century:

- 200,000 EJ of energy has entered the oceans;
- 18,000 EJ has gone into melting ice in glacial systems;
- 9,000 EJ has entered the Earth’s land surfaces;
- 7,000 EJ has entered the lower atmosphere.

For comparison, our present primary energy consumption is around 500 EJ/year, but in a business-as-usual world, is expected to grow to as much as 1000 EJ by 2050 (one EJ is equal to 10^{18} Joules) [28]. Two hundred EJ is sufficient energy to raise all of the water in Lake Erie (in the North American Great Lakes System) from 0 °C to 100 °C.

2.2.3 Greenhouse Gases and Their Anthropogenic Sources

What are the main greenhouse gases, and why have they increased rapidly over the past century? Water vapour is sometimes listed as the most important GHG, but its atmospheric concentration at any location is a function of local surface climate and its control of relative humidity levels. It is thus best considered as a feedback effect from global warming, and not as a GHG in its own right [25, 41]. Table 2.1 lists the most important GHGs, along with their human sources and Global Warming Potentials (GWPs).

Table 2.1 Greenhouse gases, anthropogenic sources, GWP, and atmospheric concentrations

Greenhouse gas	Chemical formula	Anthropogenic sources	Atmospheric concentration (2005)	GWP (20 year)	GWP (100 year)
Carbon dioxide	CO ₂	Fossil fuel combustion, cement manufacture, land use changes	379 ppm	1.0	1.0
Nitrous oxide	N ₂ O	Nitrogenous fertiliser	319 ppb	289	298
Methane	CH ₄	Gas fields and pipelines, cattle, flooded rice fields	1774 ppb	72	25
Halocarbons		Electronics industry			
CFC-11	CCl ₃ F		251 ppt	6730	4750
CFC-12	CCl ₂ F ₂		538 ppt	11,000	10,900

Source: IPCC [17]

The most important GHG is CO₂, which the IPCC estimates to be responsible for about 57 % of global warming. Most (77 %) of this CO₂ in turn comes from the combustion of fossil fuels and cement manufacture, the rest from biological sources including tropical deforestation. Its present-day concentration is nearly 390 ppm, compared with the pre-industrial value of around 280 ppm. The most important features of the global carbon cycle are shown in Figure 2.2. Note that atmospheric carbon storage is small compared to soil and ocean storage, and that the annual net additions of CO₂ to the atmosphere and oceans are only a small fraction of the total exchanges of CO₂ between the various storages.

Other important GHGs are methane, nitrous oxide, halocarbons and tropo-spheric ozone. Methane concentrations are about double their pre-industrial value, and in the last few years have risen sharply [2]. Nitrous oxide concentrations are about 50 % higher than pre-industrial times, and are rising at around 2–3 % each year [11]. These other GHGs are considered further in Section 2.4.1.

Net irradiance is the difference between the incoming and outgoing solar radiation, and this difference is largely responsible for the Earth’s climate. Radiative forcing refers to changes in this net irradiance. By stopping some of the outgoing radiation, the various atmospheric GHGs can be considered to exert a positive radiative forcing measured in W/m². For example, the latest IPCC report gives a

‘best estimate’ figure of 1.66 W/m^2 for CO_2 forcing, and 0.48 W/m^2 for methane, although the values are subject to some uncertainty. In addition, aerosols can exert a negative radiative forcing from both direct and indirect effects, thus off-setting to some extent that of these long-lived greenhouse gases. The extent of the negative forcing is very uncertain, and this uncertainty explains why overall climate sensitivity values are uncertain.

The various GHGs can be ranked according to their Global Warming Potential (GWP), using CO_2 as the standard, with a GWP of 1.0. GWPs integrate the radiative forcing over a specified time period resulting from the one-off unit mass emission of a given GHG. They can be used to compare the climate change effects of different GHGs. As shown in Table 2.1, the GWPs of the various GHGs differ at both the 20 and 100 year time horizons by four orders of magnitude. Current atmospheric concentrations vary by eight orders of magnitude [41]. Using the GWP concept, we can convert the other GHGs into CO_2 equivalents, and so calculate an equivalent CO_2 concentration in ppm that would have the same warming effect as all the GHGs acting together, abbreviated $\text{CO}_2\text{-e}$.

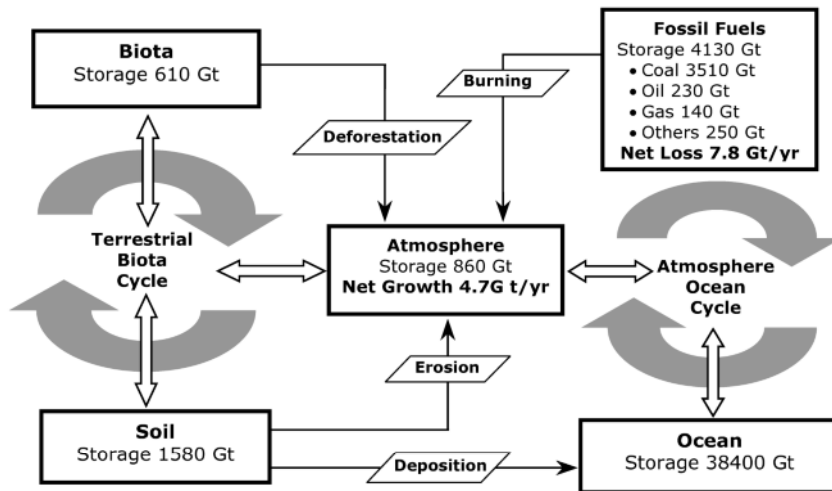


Figure 2.2 The global carbon cycle

With the exception of various industrial compounds such as the halocarbons and similar chlorine- and bromine-containing compounds, all these GHGs exist naturally. Before the Industrial Revolution, however, their concentrations were believed to be relatively stable. On longer timescales their concentrations varied. Over the recent ice ages, CO_2 concentrations varied in a cyclic manner from around 180 ppm at the height of the glacial periods to about 280 ppm during the interglacial periods. The present value of about 390 ppm is thus far outside this range. Figure 2.3 shows the rapid growth in atmospheric ppm since Keeling began direct measurements in

Mauna Loa in the late 1950s. The annual cycle shown results from the drawdown of atmospheric CO₂ in the northern growing season, and its subsequent release in the colder months. (Because most terrestrial vegetation, especially at higher latitudes where the seasonal cycle is most pronounced, is in the northern hemisphere, the counter-effect in the southern hemisphere is much smaller).

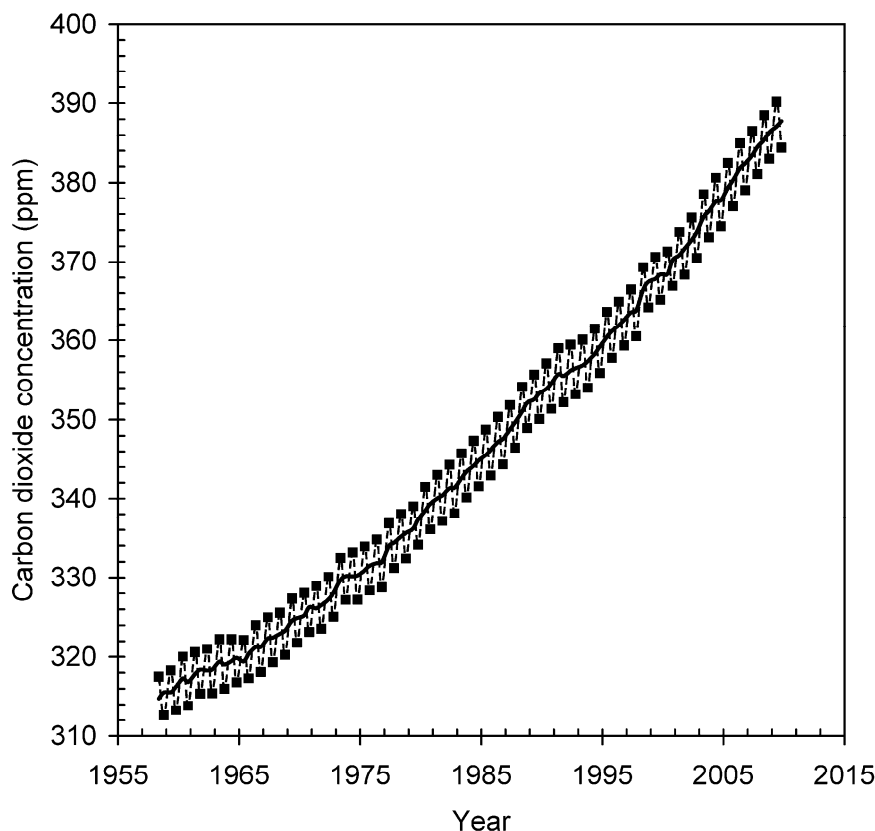


Figure 2.3 Growth of atmospheric CO₂ concentration, 1958–2009; symbols represent seasonal variation, solid line is the annual trend (1958–1974 Scripps Institution of Oceanography, 1974–2009 National Oceanic and Atmospheric Administration). Source ESRL [16]. Used with permission

A number of research papers have recently shown that it is cumulative, rather than annual, emissions of CO₂ that are crucial, because of the long residence time of CO₂ in the atmosphere [1, 5, 9, 23, 26, 27, 41]. One modelling study found that released CO₂ is mainly absorbed by the oceans over a period of 2–20 centuries, but about 20–40 % would remain in the atmosphere for far longer periods [5]. The climate effects of our present CO₂ releases will thus persist for many millennia to come. Because of its atmospheric longevity and concentration, and because most

CO₂ emissions result from fossil fuel combustion, the focus in this book's chapters on mitigation is on CO₂ reductions. Policies for reducing other GHGs are briefly examined below in Section 2.4.1.

2.2.4 Learning from the Past

In general we have two approaches available to us for our attempts to forecast where rising levels of GHGs will take us. We have already briefly mentioned global climate models and their uses, but a different approach is to use the study of the Earth's past climate history – paleoclimatology – for clues that could inform the future. Since instrumental temperature measurements only go back about one and a half centuries, we have to rely on proxy records for understanding the past. We are particularly interested in studying those periods when climates were broadly similar to today's.

Scientists have accumulated more and more proxy data about climatic conditions in the distant past from tree ring counts, ocean and lake sediment cores, ice cores from Greenland and Antarctica, as well as historical data for the more recent geological past. We can use these to determine concentrations of GHGs in the distant past, and also temperatures, sea water levels, and whether the climate was generally wet or dry. To improve accuracy, these various indirect measures are checked against each other, and if possible, against the instrumental record of the past century or so. We can find climate analogues for our present situation, and so get an alternative to climate modelling for assessing future Earth conditions. The general lesson we learn from examination of past climates is that the Earth temperature responds strongly to changes in the radiative balance.

This is not the first time Earth has seen rapid rises in CO₂ and global warming, although those in the past were from natural causes. One important example is referred to as the Paleocene-Eocene Thermal Maximum (PETM) event. As we will discuss in Chapter 4, a rapid and major release of CO₂ occurred about 55 million years ago. It caused not only global warming of about 5 °C, but also ocean acidification and mass extinctions of species [2]. Its relevance to our present condition is obvious.

One vital finding from examination of climate changes in the distant past is how severe the changes can be for global temperature changes that are forecast for this century in 'business-as-usual scenarios'. During the Pliocene epoch, 3 million years ago, the Earth was on average only 2–3 °C warmer than today, yet sea levels were 25–35 metres higher because only smaller ice sheets survived in the warmer climate. On the other hand, during the last great Ice Age, sea levels were 120 metres lower than now. The 4–7 °C drop in temperatures compared with today resulted in a transformation of Earth's surface and its ecosystems [2].

'But where are the snows of yesteryear?', lamented the renaissance French poet François Villon. Rest easy François, they're still here. Perhaps not in Paris, but in

Antarctica lie the snows of a million yesteryears. Much of our information about Earth's past climate has come from deep ice cores painstakingly recovered from the Antarctic and Greenland ice caps. Drilling and recovering a continuous core of ice enables us to work out how climate has varied over past millennia. The deeper you drill, the older is the annual snow layer which is then compacted by the weight of overlying snow to form ice. From air bubbles trapped in the ice, scientists can determine the temperature at that time by isotopic analysis of the oxygen. They can also directly measure the composition of the atmosphere at that time, and in particular the concentrations of CO₂ and CH₄. The ancient air bubbles can also reveal the amount of dust in the atmosphere, which gives us a rough idea of how dry or wet the climate was.

Changes in inferred global temperatures over this extended time period correlate very strongly with changes in atmospheric CO₂ levels. Temperature rises typically occur before the increases in atmospheric CO₂, which has led some to argue that GHGs cannot be the cause of present global warming. But as Allison and colleagues [2] point out: 'This finding is consistent with the view that natural CO₂ variations constitute a feedback in the glacial-interglacial cycle rather than a primary cause.'

The EPICA/Dome C ice cores already give us a view of climate in the Antarctic over the past 800,000 years, and show data for eight previous glacial cycles [21]. These ice cores form an ancient library of the Earth's past history. But once these and other, smaller, ice caps – particularly tropical glaciers – are destroyed by melting, the library is likewise destroyed.

From ice cores and much other evidence, we now know that over the past three million years or so, our planet has passed through a series of Ice Ages, in which global volumes of ice advanced and retreated in a regular pattern, with corresponding changes in sea levels. Astronomical factors have also been invoked to explain these recent ice ages. In the early decades of the 20th century, the Serbian engineer Milutin Milankovic refined an older theory explaining the ice ages by variations in the shape of the Earth's orbit, and in the tilt and wobble of the Earth's axis.

These variations, caused by the gravitational influence of other planets on the Earth, vary the distribution of the Sun's insolation to the Earth on cycles of varying lengths. One cycle of approximately 100,000 years length seems to match the waxing and waning of the recent ice ages. In brief, these changes in Earth's orbit are 'the pacemaker for glacial-interglacial cycles' [2]. However, these small changes are amplified by various climatic feedbacks to give the large changes we find in the proxy records we have for global temperatures and ice volumes that occur as Earth moves from glacial to interglacial periods.

Figure 2.3 shows that atmospheric CO₂ ppm have risen in a regular pattern, and it might be thought that climate will change in a similar manner. But as the science writer Fred Pearce puts it: 'Nature doesn't do gradual change' [32]. Others talk of tipping points in the climate system [2, 38]. This realisation came about for Earth scientists in the 1980s, when the results from the Greenland ice cap cores were published. What the scientists found was that abrupt swings in climate – such as a 10°C drop in temperature – could occur in as little as two decades.

More recent research has found that, at least regionally, significant change could occur in a matter of less than a year [37]. While our general circulation mathematical models do a good job of retrospectively predicting seasons on Earth, they do a poor job of predicting such abrupt climate changes. So for a fuller understanding of climate change we also need detailed studies of past climates, as well as mathematical models. Yet all our present policies regarding climate change implicitly assume that the change will be gradual, with plenty of warning.

We can also learn much that will be useful for anticipating both future challenges and how to deal with them from studying the recent, documented past. Extreme weather events like floods, droughts and heatwaves can be analysed to determine both their impacts and how successful were the human responses to them. Given that the frequency of such events is projected to rise, acquiring such knowledge for different regions is urgent [31].

2.2.5 The Polar Regions Are Critical

The two polar regions, and the Arctic in particular, are critical for several reasons. First, as predicted by climate models and as verified empirically, warming in the Arctic has been at a rate 2–3 times faster than global temperature increases overall. Some parts of the Arctic have warmed by as much as 5 °C, which is at least as much as the IPCC expect for the world overall from a doubling of atmospheric CO₂ from pre-industrial levels. The Arctic is thus a laboratory for climate change effects, helping us to anticipate the likely changes in store for the more populous regions.

First, major changes have already occurred in Arctic temperatures, snow and ice cover, and nutrient availability, which in turn have caused major ecosystem changes [36]. Lemming and other small rodent populations have crashed because of diminished protective snow cover. Insect pests are expanding northwards, and red foxes are displacing Arctic foxes. The spring melt is occurring earlier, resulting in a longer growing season for both aquatic and land ecosystems. While this can have beneficial effects, caribou calving dates have not advanced, so that calves are no longer born at the seasonal peak of food availability for caribou.

Second, warming in the Arctic is globally significant, because it may cause large releases of CO₂ and CH₄ presently safely trapped in the frozen soils of the tundra. These releases would enhance global temperature increases. Arctic warming is also the cause of the recent rapid disappearance of summer Arctic sea ice [36]. Melting sea ice doesn't contribute to sea level rise, but it does decrease the local surface albedo, as does reduction in terrestrial snow cover, since open water (and bare land or vegetation) absorb a larger fraction of the Sun's incoming radiation than ice or snow-covered surfaces. This lower albedo results in local enhanced warming on land, and subsequent permafrost degradation and GHG release.

Third, the warming is already affecting the Greenland icecap, which, if completely melted, would raise the level of the world's oceans by seven metres. Re-

cent satellite measurements suggest that both the Greenland and the Antarctic ice sheets are losing mass at an accelerating rate [20, 44]. Even if globally averaged temperatures showed little future rise, local increases at the poles could still be catastrophic for us.

James Hansen, a prominent US Earth scientist, thinks that the key issue for us is sea level change [18]. How fast can these ice sheets disintegrate? Hansen calculated that an additional global warming of 1.0°C is all we can afford if we are to avoid the eventual break-up and melting of the Greenland ice sheet. Once melting is underway, it is not easily stopped. Building up ice sheets takes millenia, as snow is added year by year, but disintegration, once started, is assisted by several feedback mechanisms, and can occur fairly rapidly. But it might, or might not, take centuries. The trouble is that we can't be sure what temperature change will occur for a given rise in CO₂ and other greenhouse gases because of the uncertain effects of feedbacks from water vapour, aerosols, and clouds. (We discuss climate uncertainty in Chapter 4).

The disappearance of all the icecap of Antarctica can be readily shown to raise sea levels globally by 52.8 metres. Complete melting of the 3 km thick Greenland ice cap would contribute 6.6 metres to sea levels, and the most vulnerable part of the West Antarctic ice sheet 3.3 metres [2]. Our far descendants may well have different lifestyles to ours, but even they probably won't want to live under ten metres or so of water. Our continued emissions of GHGs into the atmosphere clearly raises intergenerational equity issues.

2.3 What Impacts Can We Expect?

As we have just seen, one well-publicised effect of global warming is sea level rise. The severity of the changes will, in general, depend on the temperature rise. Hence changes can be expected to become more severe with time, depending, of course, on the success or otherwise of our efforts at climate mitigation. Many studies, including the 2007 IPCC report (*e.g.*, [2, 25, 31, 35, 39]) have discussed the projected impacts of future climate change in detail. The more important probable impacts discussed in these studies are summarised as follows:

- Water volumes stored in glaciers and snow cover will decline, reducing summer and autumn stream flows in many populous areas. This could be a particular problem in the Himalayas, which is the origin of many of Asia's most important rivers. Runoff and water availability will fall in much of the mid-latitudes and dry tropics, although increases can be expected at higher latitudes and some wet tropics. Drought-affected areas will rise, as will the frequency of extreme precipitation events, so that the risk of both floods and droughts will rise. (Average annual rainfall is not always a good indicator of a region's suitability for agriculture.) Extreme precipitation events will in turn lead to dispro-

portional increases in soil erosion, which along with droughts and floods, will adversely affect agricultural output.

- Sea levels will rise both because of the thermal expansion of the upper layers of the ocean, and the contribution from net loss of terrestrial ice, particularly in the Arctic. At present, thermal expansion dominates, but melting ice is predicted to dominate sea level rise in the longer term. The IPCC predicts a rise above year 2000 levels of 0.18–0.59 metres by 2100, but cautions that ‘future rapid dynamical changes in ice flow’ were not considered in arriving at this result [41]. Other researchers, on the basis of more recent data, predict much greater increases. Allison and co-workers [2] give two meters rise as an upper limit while James Hansen [18] thinks that the 21st century sea level rise will be several metres. At present, 160 million people live less than one metre above sea level. Coastal flooding will increase, as will salt water intrusion into coastal fresh water aquifers. The oceans will also become progressively more acidic as their CO₂ concentration rises, with potentially serious consequences for organisms with calcareous shells.
- Increases in the frequency and severity of heatwaves will raise human mortality in many areas, but will be offset to some extent from declining deaths from cold spells. Warmer temperatures will expand the range of many diseases and crop and forest pests. In North America, an increase in the frequency of cardio-respiratory diseases because of higher concentrations of ground-level ozone is anticipated, the latter a result of climate change. People at risk from dengue fever are projected to rise to several billion later in the century.
- In mid- to high-latitude regions, some warming will initially help cereal and pasture yields by extending the growing season, but will lower yields in warmer areas, because even minor warming will lead to rises in temperatures above the optimum for photosynthesis. In the African Sahel, yield decreases may already be occurring [25]. Further warming will lead to lower yields in all areas. The rising severity of extreme climate events, along with increasing risk from fire, pests and disease outbreaks will further lower agricultural and forest production.
- The ecological effects from global climate change are already being felt (see Section 2.2.4). For example, species are migrating polewards and to higher altitudes in response to rising local temperatures [31]. Ecosystems do have some capacity to adapt to climate and other changes, but temperatures are presently rising at several times their historical rate. Further, ecosystems face multiple stresses (*e.g.*, from pests, diseases, ocean acidification, pollution and fires) which together are likely to exceed their limits for adaptation. Sea surface temperature rises of 1–3 °C will lead to more coral bleaching and mortality. More generally, for rises of 2–3 °C above pre-industrial temperatures, 20–30 % of species will increasingly be at high risk of extinction.

Climate change is not the only factor that is causing adverse impacts on the environment. Pielke and colleagues [34] point out that, in the Philippines, excessive groundwater extraction is lowering coastal land surfaces by 1–2 orders of magnitude

each year more than that from global sea level rise. (One ‘order of magnitude’ is used to indicate an approximate factor of ten, two orders of magnitude a factor of 100, and so on.) Ground water pumping, not climate change, is thus mostly responsible for the increasing risk of coastal flooding. In many countries, the risk is increasing over time because a higher proportion of the population lives near the coast.

Malaria is another example. Pielke and colleagues report on a study which forecasts a 100 % rise in malaria by 2080 as a result of non-climate change factors (such as population increase). In contrast, climate change would only result in a 7 % rise by 2080. They conclude:

Virtually every climate impact projected to result from increasing greenhouse-gas concentrations – from rising storm damage to declining biodiversity – already exists as a major concern [34].

Their points are well-taken, but a fear with progressive rise in GHGs is that abrupt or irreversible changes in climate could occur (as borne out by the climate record), rather than the gradual changes we have come to expect.

2.4 What Should We Do?

Two approaches are possible for dealing with global climate change: mitigation and adaptation. The IPCC’s 2007 report devoted a separate volume to each of these approaches [6, 31]. Mitigation attempts to avoid the climate changes discussed above by either reducing the levels of GHG concentrations in the atmosphere, or by changing the albedo of Earth, and so counteracting the ‘forcing’ from increasing GHG concentrations. Methods for GHG reductions include more use of renewable energy, nuclear energy and energy efficiency to cut energy-related carbon emissions, together with carbon sequestration and storage to prevent the CO₂ from fossil fuel combustion and land use changes reaching the atmosphere. Adaptation, on the other hand, involves the implementation of policies to counter the expected harmful impacts of ongoing global climate change. Here we will deal with both mitigation strategies for the most important non-CO₂ GHGs, and adaptation to a changing climate.

2.4.1 Mitigation

We discuss the possible mitigation strategies in detail in Chapters 5–9, but the focus there is largely on CO₂ reductions. Production of the most important CFCs is already being phased out under the Montreal Protocol to protect the ozone layer. Hydrofluorocarbons (HFCs) are presently used to replace CFCs in refrigerators and air-conditioning units, but it is now realised that although HFCs don’t damage

the ozone layer, they are, like CFCs, many thousand times more effective than CO₂ at trapping outgoing radiation.

Velders and others [45] modelled the anticipated growth of these compounds out to the year 2050. By 2050, their results showed, annual HFC atmospheric emissions, measured on a GtCO₂-e basis (one Gt is one billion tonnes), could be 9%–19% of total CO₂-e emissions, assuming a business-as-usual scenario. Most of the high projected growth resulted from the surge in refrigerator ownership in the newly industrialising countries. From an Earth System Science viewpoint, the move to ozone-friendly refrigerants has been a mixed success.

The growth rate of atmospheric emissions of methane is the result of the balance between emissions to the atmosphere from both natural (*e.g.*, termites, wetlands, etc) and human sources, and its removal by photochemical destruction. This removal is caused by the hydroxyl radical, the leading atmospheric oxidant [8]. Growth in anthropogenic methane emissions to the atmosphere slowed during the 1990s, but growth rates have now started to rise again. This growth could be caused by reductions in hydroxyl radical levels, which would raise the lifetime of methane in the atmosphere.

Reducing the anthropogenic emissions of methane is advocated as a means of taking effective action against climate change because the atmospheric life of methane is only a decade or so, compared with the centuries-long life of CO₂. Cutting methane emissions thus promises to mitigate climate change in the short term, but only if the reductions are continued indefinitely.

Around half of all methane emissions arise from the agricultural sector, and these are anticipated by the IPCC to grow by around 60% by 2030 [6]. Better management of both livestock and their manure might reduce methane production from enteric fermentation by cattle. A more radical solution would involve the human population moving to a more vegetarian eating pattern. But flooded rice paddies also release methane; improved rice cultivation techniques could help cut their emissions.

Methane is also slowly released by garbage landfills. Using landfill methane has a double benefit: it not only directly lowers the release of an effective GHG, but, when used as a source of energy, also reduces fossil fuel combustion. However, it is variable in both calorific content and production rate, making its use difficult in gas grids. Natural gas is presently enjoying the fastest growth of any fossil fuel, which will tend to increase methane releases from natural gas fields and gas pipelines. There is scope for reductions from these sources, but in any case, natural gas has far lower CO₂ releases per unit of energy than other fossil fuels.

About 60% of N₂O emissions comes from agriculture. Because of the need for greatly increased agricultural output to meet the needs of a rising population, the IPCC [6] expect agricultural N₂O emissions to grow by 35%–60% by 2030. The timing and amount of nitrogenous fertiliser applications to soils can be improved both to cut emissions of N₂O and reduce water pollution. Nevertheless, conflicts can occur between the need to reduce N₂O emissions and the need to enhance agricultural output per hectare in the face of declining land availability and soil erosion losses.

2.4.2 *Adaptation*

Adaptation to adverse climatic conditions is hardly a new idea. Irrigation can compensate for low rainfall, air-conditioning can maintain human comfort levels in the face of high temperatures. Crops are already adapted to the area in which they are grown; tropical fruits are not grown in the orchards of northern Europe, for example. As we have seen, climate change will, initially at least, hit hardest in the tropics, if only because crops there are already close to their optimal level for photosynthetic activity [25]. At the same time, the technical and organisational capacity for adaptation is often low in tropical countries, especially the poorest of them. Adaptation as the main global policy for responding to climate change runs the risk of placing the costs of adverse climate change on the poorest countries, despite most of the cumulative emissions having come from the industrial countries. Mitigation policies, in contrast, will, initially at least, target high per capita emitters, as in the Kyoto Protocol.

Adaptation to climate change has started, and will continue, with many countries already factoring climate change into their water supply plans and coastal sea defence systems. Even if the world soon starts to dramatically reduce its annual GHG emissions, global temperatures will continue to rise, for two reasons. First, if we stopped all emissions today, temperatures would continue to rise for decades because of the thermal inertia of the oceans, which represent an enormous heat sink. This committed rise is estimated to be about 0.6°C [35] in addition to the 0.76°C that has already occurred.

Second, institutional inertia will ensure that emissions at some level will continue for decades to come. The world economy is over 80 % powered by fossil fuels, and their share is still rising. Fossil fuel infrastructure represents a very large and still rising investment, and is long-lived – coal power stations can last a half-century or so. If all fossil fuel power stations, in operation, under construction, or planned, are used to the end of their economic lives, very large increases in atmospheric CO_2 concentrations will result.

As we will discuss in more detail in Chapter 3, climate change is only one of the drivers of the adverse environmental changes we face. Hence the capacity for adapting to future changes from any cause needs to be enhanced. But adaptation also has its limits. As climatologist Michael Mann [25] points out, reliance on adaptation as the main or even only strategy would be risky, since in most future emissions scenarios, ‘many of the predicted climate-change impacts are also likely to exceed the capacity for humans (or ecosystems, for that matter) to adapt.’ Also, we would increasingly have to adapt to rapidly changing conditions, and even abrupt changes, if we do not make massive attempts at climate change mitigation. For adaptation to work, we have to know what we are adapting to. Thus adaptation is a slippery slope, since if we commit ourselves to it as our main strategy, we may not be able to mitigate the change in climate if our ability to adapt to climate change diminishes.

2.5 Climate Change, the Public and Policy-making

So far, we have looked at the science of global climate change and the greenhouse gases responsible for the changes. The overwhelming majority of climate scientists consider that continued accumulation of GHGs in the atmosphere will lead to corresponding average surface temperature increases. As evidenced by the progressively stronger language of the four IPCC reports from 1991 to 2007, their confidence in the reality of global warming is rising. We have also analysed the serious changes likely to result as our planet progressively warms, and how we must respond. Nevertheless, scientists have not been successful in communicating this urgency to the general public or their policy-makers. Why is this the case, and what can be done to rectify this situation? How can we develop policy responses that match the gravity of the climate change problem?

Evidence for the polarisation of the controversy among the reading public can be obtained from the Amazon books website [3]. In early 2010, the entry 'global warming' produced almost 4,500 hits and 'global climate change' over 2,500 hits for books available from Amazon which at least mentioned this topic. Both sides of the controversy are represented, with 32 books discussing the term 'global warming myth' and 24 books discussing the 'global warming hoax'. Despite the small number of titles, books by sceptics sell well; an earlier search in 2002 found that the two top-selling books had sales of 176 thousand for climate sceptic Fred Singer (compared with 128 thousand copies for environmentalist Jeremy Leggett). This website also showed that those buying books on this topic don't seem to read books from the other side of the controversy, as evidenced by the lists provided by the Amazon website of other books they purchased [29].

These readership numbers contrast sharply with the reviewed literature. 'Google Scholar', which lists scholarly articles, gave only a few hundred entries for 'global warming skeptics' and 'global warming hoax' combined in early 2010. The term 'global warming', on the other hand, produced over 400 thousand hits. Very few articles in the peer-reviewed scientific literature are by global warming sceptics, as distinct from controversies among climatologists themselves, who accept the reality and seriousness of global climate change, but argue about the interpretation of model results, for example.

Other research has found that support for the reality of serious climate change varies with knowledge regarding climate change. A 2008 survey in the US found that such support among all Earth scientists polled was 82 %, but among climatologists only, the figure rose to 97.4 %. A Gallup poll survey of the general public suggested that only 58 % would have responded positively [13]. Furthermore, anthropogenic climate change is supported by the academies of sciences of many countries, including all those with major Earth science research programs [12].

This still leaves open the question of why public support on this question is so much lower than it is for climate experts. Public support for the reality of serious climate change appears to be subject to the availability effect. For example, when

the public is polled on which mode is safer on a fatalities per million passenger-km basis, many respond that cars are safer, because of the vivid images conjured up by major air disasters. In fact commercial air travel is far safer [47]. Similarly, in Europe, surveys reveal that public belief in climate change varies with average summer temperatures.

Based on a survey in the south of England, Lorraine Whitmarsh [46] stated the problem bluntly:

Overall, the findings show a tendency for the public to dissociate themselves from the causes, impacts, and responsibility for tackling climate change/global warming.

Lorenzoni and Hulme [22] surveyed attitudes in Italy and the UK, and found that providing information on climate change in order to change public attitudes and behaviours had enjoyed limited success. These and other surveys suggest that public scepticism may well result from an appreciation of the major changes needed if climate change is to be effectively tackled. The general acceptance of an anthropogenic cause of stratospheric ozone depletion supports this idea; alternatives to CFCs were available and at an acceptable cost. Phasing CFCs out thus had negligible overall economic impact.

Many blame the media for presenting a biased view on climate change, charging that they under-play the near consensus among climate scientists discussed above. However, as Boykov and Boykov [7] have argued, media reportage on climate change has consistently adhered to journalistic norms of ‘personalization, dramatization and novelty’, and that it is these norms that have hindered the understanding of the issue by the public. The aims of the various media and scientists only partly overlap on the climate question.

Other groups with a keen interest in the issue are the energy intensive industries, and, of course, the fossil fuel energy companies themselves. These corporations, and their shareholders, have much to lose if limits are put on CO₂ emissions, or if heavy carbon taxes are implemented. In the 1990s and early years of the 21st century, their approach was to fund climate sceptics and to found groups opposed to the reality of global warming, such as the ‘cooler heads coalition’ [29]. More recently, their tactics appear to have shifted. Many coal mining companies now support ‘clean coal’, by which they mean carbon capture and sequestration (see Chapter 8). In general, big industry has appropriated the word ‘green’ which is now used to describe hybrid cars, more efficient appliances, corn-based ethanol and so on.

In summary, it is not surprising that the public, even in OECD countries, has a poor understanding of the science of global climate change. The topic is a very complex one to understand, as climate scientists themselves readily acknowledge. The media do not help, favouring controversy over an understanding of the issues. The low level of basic science understanding in most countries, even those of the OECD, is a further barrier. Industries initially saw their self-interest as supporting climate sceptics, and in general opposing attempts to lower fossil fuel emissions,

or at least fossil fuel use. In Al Gore's famous summary, global warming is 'An Inconvenient Truth'. In more recent times, the industry approach has moved to at least verbal support of climate change mitigation policies. Many oil exporting countries, however, continue to deny the reality of global climate change.

2.6 Closing Comments

Significant global climate change has already occurred, and the problem is not going to go away. The CO₂ we have released over the past century or so will remain in the atmosphere for centuries, even millennia, to come. The response of the global climate system to given changes in concentrations of heat absorbing GHGs is obviously a question that is best addressed by climatologists, but clear-cut answers are hard to come by. The topic is extremely complex, with the climate system exhibiting multiple feedbacks, both positive and negative, operating at different timescales.

The observed change in climate is not regular; it proceeds in a jerky fashion, as evidenced by the year-to-year ups and downs in global average surface temperatures. This internal climate variability makes it very difficult to unambiguously ascribe observed anomalous climate patterns in the short term, for example, the decrease in rainfall in Eastern Australia in recent decades, or the European heatwave in 2003, to climate change. It also allows scepticism to flourish.

Global climate change policies must have an ethical component. At least for the medium term, poor countries will bear the brunt of adverse climate change, for two reasons. First, most of the world's poor live in the tropics, which is expected to experience declines in agricultural output. Such declines could be catastrophic for the many largely agricultural countries with still-rising populations. Second, low income countries have neither the financial resources, nor, in many cases, the administrative capacity, to successfully adapt to rapid climate change. As stressed by climatologist Michael Mann [25], ongoing climate change will see a net redistribution of resources, mainly from the low- to the high-income countries. A stress on individual country adaptation, rather than on mitigation, will worsen this inequality in consequences.

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