Rep. Prog. Phys. **68** (2005) 1343–1403 doi:10.1088/0034-4885/68/6/R02

Global warming

John Houghton

Hadley Centre, Meteorological Office, Exeter EX1 3PB, UK

Received 10 January 2005
Published 4 May 2005
Online at stacks.iop.org/RoPP/68/1343

Abstract

'Global warming' is a phrase that refers to the effect on the climate of human activities, in particular the burning of fossil fuels (coal, oil and gas) and large-scale deforestation, which cause emissions to the atmosphere of large amounts of 'greenhouse gases', of which the most important is carbon dioxide. Such gases absorb infrared radiation emitted by the Earth's surface and act as blankets over the surface keeping it warmer than it would otherwise be. Associated with this warming are changes of climate. The basic science of the 'greenhouse effect' that leads to the warming is well understood. More detailed understanding relies on numerical models of the climate that integrate the basic dynamical and physical equations describing the complete climate system. Many of the likely characteristics of the resulting changes in climate (such as more frequent heat waves, increases in rainfall, increase in frequency and intensity of many extreme climate events) can be identified. Substantial uncertainties remain in knowledge of some of the feedbacks within the climate system (that affect the overall magnitude of change) and in much of the detail of likely regional change. Because of its negative impacts on human communities (including for instance substantial sea-level rise) and on ecosystems, global warming is the most important environmental problem the world faces. Adaptation to the inevitable impacts and mitigation to reduce their magnitude are both necessary. International action is being taken by the world's scientific and political communities. Because of the need for urgent action, the greatest challenge is to move rapidly to much increased energy efficiency and to non-fossil-fuel energy sources.

0034-4885/05/061343+61\$90.00

Contents

1. Introduction

There is a large literature on global warming. The most comprehensive reference and literature survey is provided by the Reports of the Intergovernmental Panel on Climate Change (IPCC) [1]—see section 9.1. A general source describing the science, impacts and policy options is my textbook *Global Warming: the Complete Briefing* [2]. This report is heavily dependent on the 2001 IPCC reports updated as necessary through reference to more recent literature.

1.1. What is global warming?

Global warming has become familiar to many people as one of the most important environmental issues of our day. This review will describe the basic science of global warming, its likely impacts both on human communities and on natural ecosystems and the actions that can be taken to mitigate or to adapt to it. As commonly understood, global warming refers to the effect on the climate of human activities, in particular the burning of fossil fuels (coal, oil and gas) and large-scale deforestation—activities that have grown enormously since the industrial revolution, and are currently leading to the release of about 7 billion tonnes of carbon as carbon dioxide into the atmosphere each year together with substantial quantities of methane, nitrous oxide and chlorofluorocarbons (CFCs). These gases are known as *greenhouse gases*.

The basic principle of global warming can be understood by considering the radiation energy from the sun that warms the Earth's surface and the thermal radiation from the Earth and the atmosphere that is radiated out to space. On average, these two radiation streams must balance. The *greenhouse effect* arises because of the presence of greenhouse gases in the atmosphere that absorb thermal radiation emitted by the Earth's surface and, therefore, act as a blanket over the surface (figure 1). It is known as the greenhouse effect because the glass in a greenhouse possesses similar properties to the greenhouse gases in that it absorbs infrared radiation while being transparent to radiation in the visible part of the spectrum. If the amounts of greenhouse gases increase due to human activities, the basic radiation balance is altered. The balance can be restored through an increase in the Earth's surface temperature.

The effect was first recognized by the French scientist Jean-Baptiste Fourier in 1827 [3]. A British scientist, John Tyndall around 1860 measured the absorption of infrared radiation by carbon dioxide and water vapour and suggested that a cause of the ice ages might be a decrease in the greenhouse effect of carbon dioxide. It was a Swedish chemist, Svante Arrhenius in 1896 who first calculated the effect of increasing concentrations of greenhouse gases; he estimated that doubling the concentration of carbon dioxide would increase the global average temperature by 5–6˚C. As we shall see later this estimate is not too far from our present understanding.

We have been familiar for a long time with problems of *air quality* caused by the emissions of pollutants such as the oxides of nitrogen or sulfur into the atmosphere from local sources. That is *local pollution*. Measures to reduce such pollution especially in major cities are actively being pursued. Global warming is an example of *global pollution*. Because of the long life time in the atmosphere of many greenhouse gases such as carbon dioxide, their effects impact on everyone in the world. Global pollution can only be countered by global solutions.

The following sections will address the basic science of the greenhouse effect (2), climate variability evidenced by past records (3), sources and sinks of greenhouse gases (4), the concept of radiative forcing and how it is used (5), climate models and how well they simulate past and current climate (6), projections of climate change over the 21st century (7), impacts of climate change especially those on human communities (8), international policy and action regarding

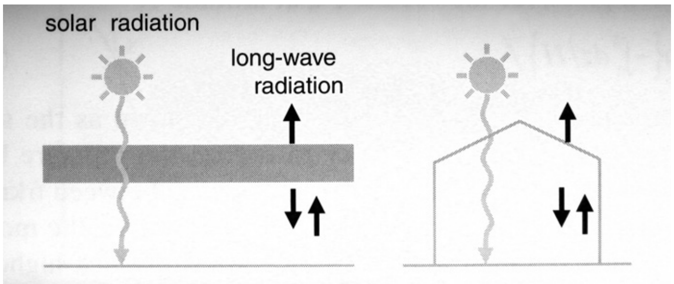

Figure 1. A greenhouse has a similar effect to the atmosphere on the incoming solar radiation and the emitted thermal radiation.

climate change, including the work of the IPCC (9), stabilization of climate (10), mitigation of climate change and implications for technology (11) and the future challenge (12).

2. The scientific background

2.1. A simple model

How the blanketing by greenhouse gases is effective can be illustrated by considering a black surface at temperature T_s receiving radiation in the visible part of the spectrum of magnitude σT_0^4, where σ is Stefan's constant. In the absence of any blanketing, at equilibrium $T_s = T_0$. Suppose, above the surface, there is inserted an absorbing layer at temperature T_a, which is transparent to the incident visible radiation but absorbs at all infrared wavelengths a fraction k of the radiation from the underlying surface. Because surfaces that absorb also emit, the layer will radiate energy of magnitude $k\sigma T_a^4$ both upwards and downwards. Considering the radiative equilibrium of the layer, it is easy to see that its temperature is given by $T_a^4 = 0.5kT_s^4$. Considering the radiative equilibrium of the surface we find that its temperature is given by

$$T_s^4 = (1 - 0.5k)^{-1} T_0^4.$$

For $k = 0.5$, $T_s^4 = 1.33\ T_0^4$. A thin layer that absorbs half the thermal radiation it receives will, therefore, increase the absolute temperature of the underlying surface by about 7.5%. For a surface originally at a temperature of 260˚C this means an increase of 20˚C.

If it is imagined that the absorbing layer is introduced instantaneously, before the surface or the layer have had time to warm, an immediate reduction occurs in the outgoing radiation at the top of the atmosphere (i.e. above the absorbing layer) amounting to $0.5\,k\sigma T_0^4$. This quantity is called the *radiative forcing* (see section 5).

As we shall see later, this very simple model with $k = 0.5$ is a crude approximation to the effect of greenhouse gases in the atmosphere on the surface temperature and on the outgoing radiation at the top of the atmosphere.

2.2. The radiation balance of Earth and atmosphere

This is illustrated in figure 2, which shows the components of the radiation that on average enter or leave the Earth's atmosphere and make up its radiation budget. The incoming solar radiation must, on average, be balanced by thermal radiation leaving the atmosphere or the surface.

Incident at the top of the atmosphere on a surface of one square metre directly facing the sun is about 1370 W. The average over the whole Earth's surface is one quarter of this or 342 Wm^{-2}. About 30% of the incoming solar radiation on average is reflected or scattered back to space

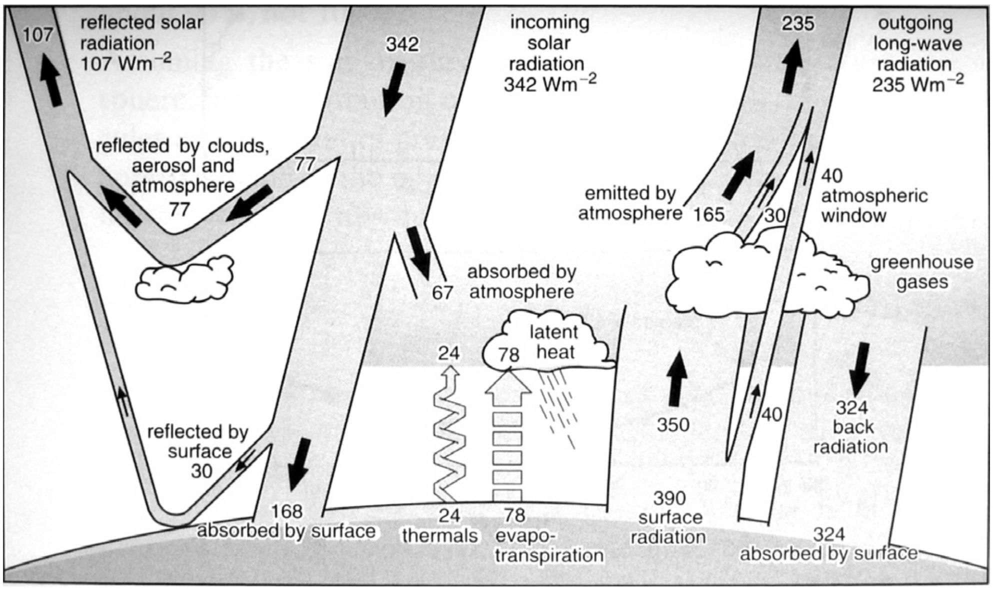

Figure 2. The Earth's radiation and energy balance [4]. The net incoming solar radiation of 342 Wm^{-2} is partially reflected by clouds and the atmosphere, or at the surface where 49% is absorbed. That heat is returned to the atmosphere, some as sensible heat but most from evaporation and transpiration (taken together these are known as evapotranspiration), which is later released as latent heat of condensation within the atmosphere. The rest is radiated as thermal radiation from the surface much of which is absorbed by the atmosphere or by clouds that also emit radiation both upwards and downwards. Part of the infrared radiation that is lost to space comes from cloud tops and parts of the atmosphere that are much colder than the surface.

from the Earth's surface, from clouds, small particles (known as aerosols) or by Rayleigh scattering from molecules.

Details of the spectral distribution of the thermal radiation leaving the top of the atmosphere in the infrared part of the spectrum can be measured from instruments mounted on orbiting satellites. In figure 3 radiation from the main greenhouse gases, water vapour, carbon dioxide, methane, ozone and nitrous oxide, can be identified.

2.3. The natural greenhouse effect

The gases nitrogen and oxygen that make up the bulk of the atmosphere neither absorb nor emit thermal radiation. If they were the only atmospheric constituents there would be no clouds and no greenhouse effect. In this case, to realize radiative balance, the average Earth's surface temperature would be about −6˚C. In fact the average surface temperature is about 15˚C. The difference between these two figures of about 20˚C is because of the *natural greenhouse effect* due to the natural abundances of the greenhouse gases, water vapour, carbon dioxide, ozone, methane and nitrous oxide. Of these gases, the largest greenhouse effect is due to water vapour and the second largest to carbon dioxide. The natural greenhouse effect is clearly vital in maintaining the Earth's climate as we know it, with its suitability for human life to flourish.

The size of the natural greenhouse effect is dependent on the temperature structure of the atmosphere above the surface where the blanketing gases are located. In the crude calculation of section 2.1, the temperature of the absorbing layer above the surface is determined by radiative transfer processes alone. However, in the lower atmosphere up to about 10 km altitude,

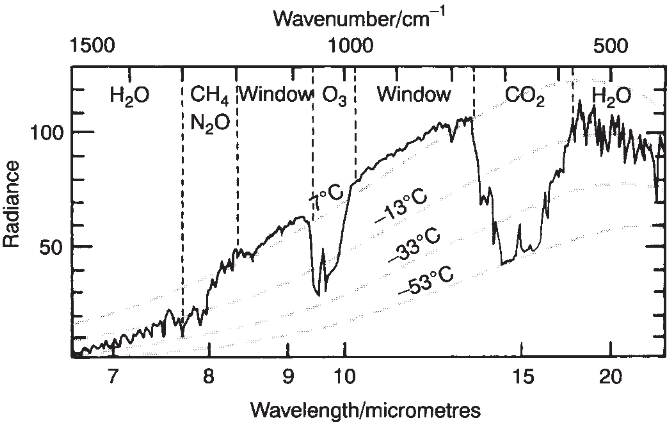

Figure 3. Thermal radiation in the infrared (the visible part of the spectrum is between about 0.4 and 0.7 μm) emitted from the Earth's surface and atmosphere as observed over the Mediterranean Sea from a satellite instrument orbiting above the atmosphere, showing the parts of the spectrum where different gases contribute to the radiation [5]. Between wavelengths of about 8 and 14 μm, apart from the ozone band, the atmosphere, in the absence of clouds, is substantially transparent; this part of the spectrum is called a 'window' region. Superimposed on the spectrum are curves of radiation from a black body at 7°C, −13°C, −33°C and −53°C. The units of radiance are Wm^{-2} per steradian per wavenumber.

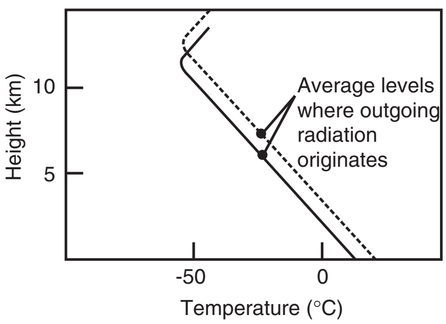

Figure 4. The distribution of temperature in a convective atmosphere (——). The dotted line shows how the temperature increases when the amount of carbon dioxide present in the atmosphere is increased (in the diagram the difference between the lines is exaggerated—for instance, for doubled carbon dioxide in the absence of other effects the increase in temperature is about 1.2°C). Also shown for the two cases are the average levels from which thermal radiation leaving the atmosphere originates (about 6 km for the unperturbed atmosphere).

the dominant processes of heat transfer are mixing and convection. That is why it is known as the troposphere (or turning sphere). Because rising air expands, it cools, and the temperature in the troposphere falls, on average, at about 6°C per kilometre of altitude (figure 4).

Radiation is emitted out to space by the greenhouse gases from levels in the troposphere typically between 5 and 10 km altitude (figure 4). Here, the temperature is much lower—by 30°C to 50°C or so—than at the surface. The radiation emitted by the gases to space is, therefore, much less than what they absorb from the radiation emitted by the surface. Note that as the blanket becomes thicker, it becomes warmer below the blanket, but the top of the blanket becomes colder.

Clouds also play a significant part in the Earth's radiation balance (figures 2 and 16). They reflect some of the incident radiation from the sun back to space. However, they also absorb and emit thermal radiation and have a blanketing effect similar to that of the greenhouse gases (see section 6). Careful consideration of these two effects shows that, on average, the net effect of clouds on the total budget of radiation results in a slight cooling of the Earth's surface.

2.4. Other planets

Similar greenhouse effects also occur on our nearest planetary neighbours, Mars and Venus, both of which possess atmospheres with carbon dioxide as the main constituent. Venus, about the same size as the Earth, possesses an atmospheric pressure at its surface of about 100 times that on the Earth. This generates a very large greenhouse effect resulting in a surface temperature of about 500˚C—a dull red heat. What has occurred on Venus is an example of what has been called the *'runaway' greenhouse effect*. Being closer to the sun than the Earth, during its early history, water vapour, a powerful greenhouse gas, would have been a dominant constituent of the atmosphere. Its strong greenhouse effect would have exerted a large positive feedback and led to all the water boiling away from the surface. There is no possibility of such runaway greenhouse conditions occurring on the Earth.

2.5. The enhanced greenhouse effect

After our excursion to Mars and Venus, let us return to Earth! To what extent are the greenhouse gases in the Earth's atmosphere influenced by human activity? The amount of water vapour depends mostly on the temperature of the surface of the oceans; most of it originates through evaporation from the ocean surface and is not influenced directly by human activity. Carbon dioxide is different. Its amount has increased substantially—by over 30 per cent—since the Industrial Revolution, due to human industry and also because of the removal of forests (see section 4). Future projections are that, in the absence of controlling factors, its rate of increase will accelerate and its atmospheric concentration will double from its pre-industrial value within the next hundred years (see section 7).

This increased CO_2 is leading to global warming of the Earth's surface through its enhanced greenhouse effect. Let us imagine, for instance, that the amount of CO_2 in the atmosphere suddenly doubled, everything else remaining the same (figure 5). What would happen to the numbers in the radiation budget presented earlier (figure 2)? The solar radiation budget would not be affected. But the thermal radiation emitted from CO_2 in the atmosphere will originate on average from a higher and colder level than before (figure 4). The thermal radiation budget will, therefore, be reduced, the amount of reduction being about $4\,W\,m^{-2}$ (see section 5) [6].

To restore the radiation balance the surface and lower atmosphere will warm. If nothing changes apart from their temperature—in other words, clouds, water vapour, ice and snow cover and so on, are all the same as before—a radiative transfer calculation indicates that the temperature change would be about 1.2˚C.

In reality, of course, many of these other factors will change, some of them in ways that add to the warming (positive feedbacks), others in ways that reduce the warming (negative feedbacks). The situation is, therefore, much more complicated than this simple calculation; it will be considered in more detail in section 6. Suffice it to say here, that the best estimate, at the present time, of the increased average temperature of the Earth's surface if CO_2 levels were to be doubled is about twice that of the simple calculation: 2.5˚C. As the next section will illustrate, for the global average temperature this is a large change.

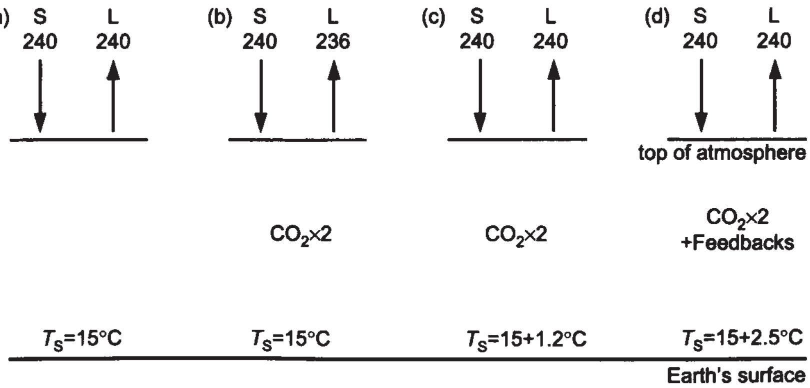

Figure 5. Illustrating the enhanced greenhouse effect. Under natural conditions (*a*) the net solar radiation coming in ($S = 240\,\mathrm{W\,m^{-2}}$) is balanced by thermal radiation (L) leaving the top of the atmosphere; average surface temperature (T_s) is 15˚C. If the carbon dioxide concentration is suddenly doubled (*b*), L is decreased by $4\,\mathrm{W\,m^{-2}}$. Balance is restored if nothing else changes (*c*) apart from the temperature of the surface and lower atmosphere, which rises by 1.2˚C. If feedbacks are also taken into account (*d*) the average temperature of the surface rises by about 2.5˚C.

Having dealt with a doubling of the amount of CO_2, it is interesting to ask what would happen if the CO_2 amount were reduced. Because, with the amount of CO_2 currently present in the atmosphere, over much of the spectral region of importance the absorption is virtually saturated (figure 3), the dependence of absorption on the gas concentration is approximately logarithmic. If, therefore, the CO_2 concentration were halved, the outgoing radiation would be reduced by about $4\,\mathrm{W\,m^{-2}}$ and the Earth would cool by about 2.5˚C. If CO_2 were to be removed altogether, the change in outgoing radiation would be around $25\,\mathrm{W\,m^{-2}}$—six times as big—and the amount of temperature change would be similarly increased.

3. The past climate record

It is important to put recent changes in climate in the context of climatic history in the past. The next three sections review the past century, millennium and million years.

3.1. The 20th century

For the last 140 years, direct instrumental data have been available that enable a construction to be made of changes in the global near-surface air temperature [7] (figure 6(*a*)). The increase in temperature over the 20th century is particularly striking. The 1990s are *very likely*[1] to have been the warmest decade during this period and the year 1998 the warmest year. A more striking statistic is that each of the first eight months of 1998 was the warmest of those months in the record. Although there is a distinct overall trend, the increase is by no means uniform. In fact, some periods of cooling as well as warming have occurred and an obvious feature of the record is the degree of variability from year to year and from decade to decade. An obvious question to ask is whether the effects of human activities are significant against the

[1] In the IPCC 2001 Report expressions of certainty such as 'very likely' were related so far as possible to quantitative statement of confidence, *virtually certain* (greater than 99% chance that a result is true), *very likely* (90–99% chance), *likely* (66–90% chance), *medium likelihood* (33–66% chance), *unlikely* (10–33% chance), *very unlikely* (1–10% chance), *exceptionally unlikely* (less than 1% chance).

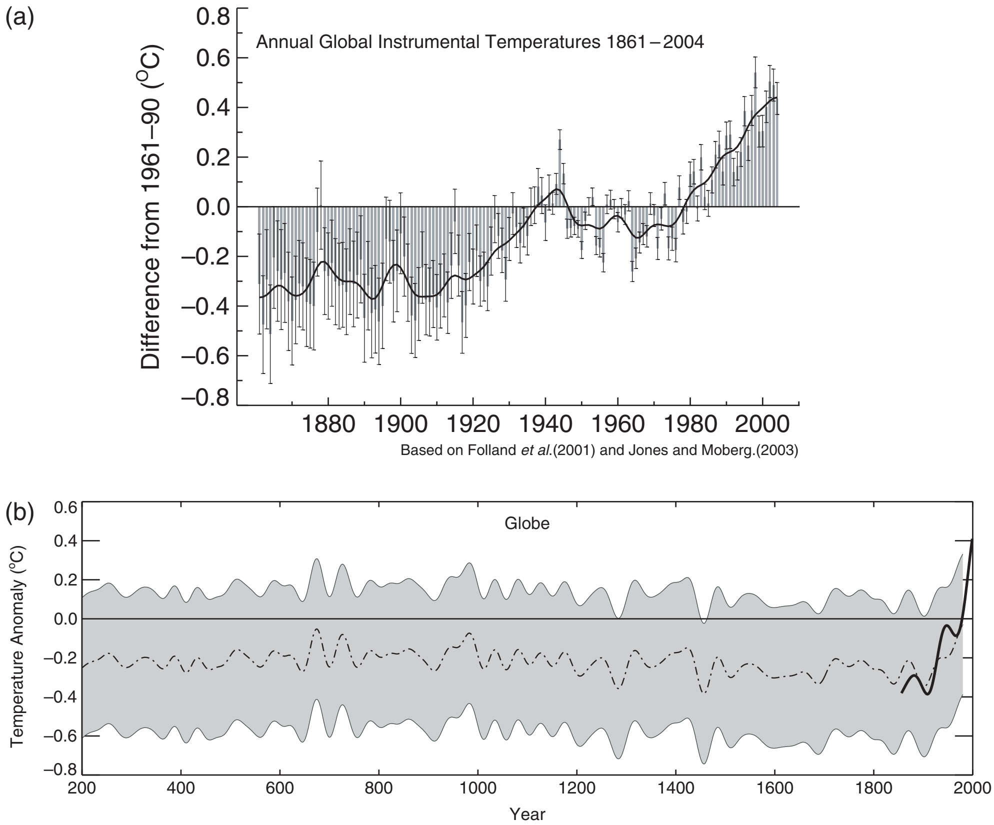

Figure 6. (*a*) Variations in the globally averaged near-surface air temperature over the last 140 years [8]. The grey bars are the year by year averaged values; the dark line is a smoothed annual curve to illustrate decadal variations. Uncertainties in the data are also shown; the thin whiskers represent the 95% confidence range. (*b*) Globally averaged temperature reconstructions for the period 200–2000 AD based on proxy data [9]. Anomalies referred to the 1961–1990 average are shown. The smoothed instrumental record for the past 140 years is shown as a dark line. The shading indicates the 95% confidence limits for the reconstructions from proxy data.

background of natural variability. In section 6 (figure 17), this question is addressed together with the likely reasons for the 20th century trends.

For an understanding of the global warming issue, of most interest is the period of the last 50 years during which greenhouse gases increased substantially (see section 4) as did the global average temperature—by about 0.5˚C [10]. Note that for the global average, this is a large change. As we shall see in section 7, some of the details of climate change over this period provide clues that link it with what is likely to occur with an increase of greenhouse gases (see section 7). For instance, the greatest warming has occurred over continents especially at high latitudes. Precipitation has also increased and some extreme events appear to have increased in both number and intensity.

In section 2.5, it was stated that, for doubled carbon dioxide in the atmosphere under equilibrium conditions, a rise in global average surface temperature of about 2.5˚C would be expected. The increase in carbon dioxide since the pre-industrial period of nearly 35% together with increases in other gases (see section 4) translates into a temperature rise of about 1.4˚C, about twice the rise of 0.6˚C or 0.7˚C that has actually occurred. The reason for the difference

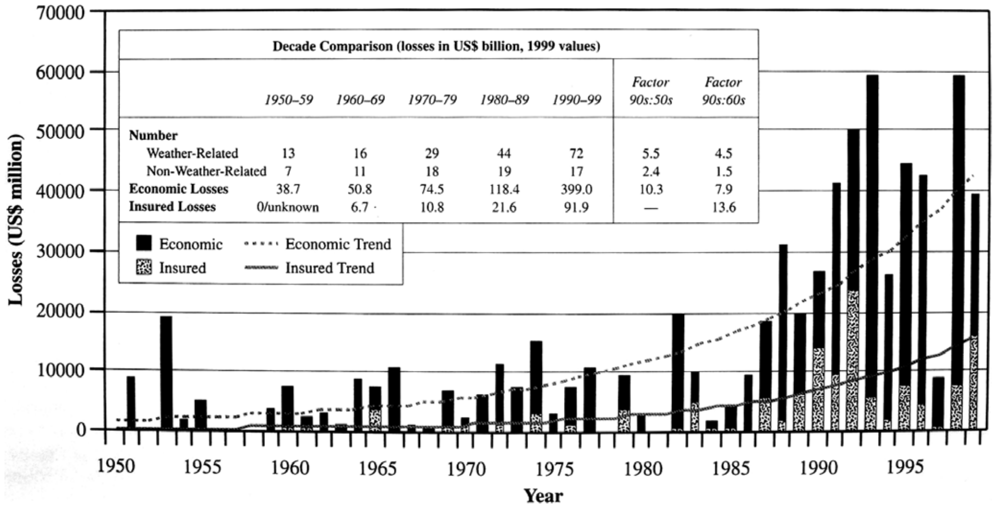

Figure 7. The total economic costs and the insured costs of catastrophic weather events for the second half of the 20th century as recorded by the Munich Re insurance company [13]. Both costs show a rapid upward trend in recent decades. The number of non-weather-related disasters is included for comparison.

is the thermal capacity of the oceans that is introducing a lag in response, with the present rate of increase of greenhouse gases of around 30 or 40 years [11]. Recent measurements of the change in heat content of the oceans down to 3 km depth from 1955 to 1998 confirms that the oceans are warming. Their heat content has increased by about 14.5×10^{22} J corresponding to a mean temperature increase of 0.037°C and an increase of energy entering the oceans averaging $0.20\,\mathrm{W\,m^{-2}}$ (per unit area of Earth's total surface area) [12].

Most of the worst disasters in the world are, in fact, weather—or climate-related—tropical cyclones (called hurricanes or typhoons), floods, wind-storms, tornadoes and droughts whose effects occur more slowly, but which are probably the most damaging disasters of all. Figure 7 shows the costs of weather related disasters[2] over the past 50 years as calculated by the insurance industry that has been hard hit by recent disasters. It shows an increase in economic losses in such events by a factor of over 10 in real terms between the 1950s and the 1990s. Some of this increase can be attributed to the growth in population in particularly vulnerable areas and to other social or economic factors; the world community has undoubtedly become more vulnerable to disasters. However, a significant part of it has also arisen from increased storminess in the late 1980s and 1990s compared with the 1950s (adequate data are not available for meaningful comparisons to be made with earlier times).

3.2. The last thousand years

For the period from 200 to 1000 AD, a number of reconstructions of global average surface temperature data have been made from proxy sources such as tree rings, corals, ice cores and historical records; an example is shown in figure 6(*b*). In order to enable data from multi-proxy sources to be analysed and merged into a consistent record, data from each proxy source is 'calibrated' by making comparisons between data from different sources and also comparing

[2] Including windstorms, hurricanes or typhoons, floods, tornadoes, hailstorms, blizzards but not including droughts because their impact is not immediate and occurs over an extended period.

them with data from instrumental sources during the period when both are available. There has been considerable debate within the literature regarding the statistical procedures that have been employed and the appropriate level of uncertainty that should be attached to the record [14].

The records indicate a lot of natural climate variability, much of which probably arises from internal variations within the climate system rather than from changes in external forcing (although see section 5). In the global record of figure 6(*b*) it may be just possible to identify regional variations within the northern hemisphere commonly known as the 'Medieval Warm Period' associated with the 11th to 14th centuries and a relatively cool period known as the 'Little Ice Age' associated with the 15th to 19th centuries. Such variations appear more prominently in the most recent reconstruction for the northern hemisphere [15] and in more local records.

What appears most dominant in figure 6 is the unusual warming of the 20th century compared with earlier centuries of the last millennium. The rate of warming in the late 20th century and the global average temperature at the end of the century are both greater than at any other time in the period. As we shall show in section 6, only anthropogenic forcing of climate can explain this recent anomalous warming.

3.3. The last million years

A particularly valuable information source about climate variations over the last million years is the record stored in the ice that caps Greenland and the Antarctic continent. These ice caps are several kilometres thick. Snow deposited on their surface gradually becomes compacted as further snow falls. The ice moves steadily downwards, eventually flowing outwards at the bottom of the ice-sheet. Ice near the top of the layer has been deposited fairly recently; ice near the bottom fell on the surface many tens or hundreds of thousands of years ago. Deep cores have been drilled out of the ice at several locations in both Greenland and Antarctica. At Russia's Vostok station in east Antarctica, for instance, where drilling has been carried out for over twenty years, the most recent core reached a depth of over 3.5 km; the ice at the bottom fell as snow on the surface of the Antarctic continent over 400 000 years ago.

Small bubbles of air are trapped within the ice enabling the composition of the air at the time at which the ice was formed to be deduced. Further information is provided by analysis of the ice itself. The ratios of the different oxygen isotopes (^{18}O and ^{16}O) depend sensitively on the temperatures at which evaporation and condensation took place for the water in the clouds from which the ice originated. These, in turn, are dependent on the average temperature near the surface of the Earth. A temperature record for the polar regions can, therefore, be constructed from analyses of the ice cores. The associated changes in global average temperature are estimated to be about half the changes in the polar regions.

Such a reconstruction from a Vostok core for the temperature and the CO_2 content is shown in figure 8 for the past 160 000 years, which includes the last major ice age that began about 120 000 years ago and began to come to an end about 20 000 years ago. It also demonstrates the close connection between temperature and carbon dioxide concentrations. Similar close correlation is found with the methane concentration. Note from figure 13 the likely growth of atmospheric CO_2 during the 21st century taking it to levels that are unlikely to have been exceeded during the past 20 million years.

A feature of the data shown in figure 8, especially when data with higher resolution in time are examined, is that the climate of the past few thousand years seems relatively stable compared with that earlier in the record where substantial and rapid variations in temperature frequently occur. Much interest is being shown in these and the possible links they might

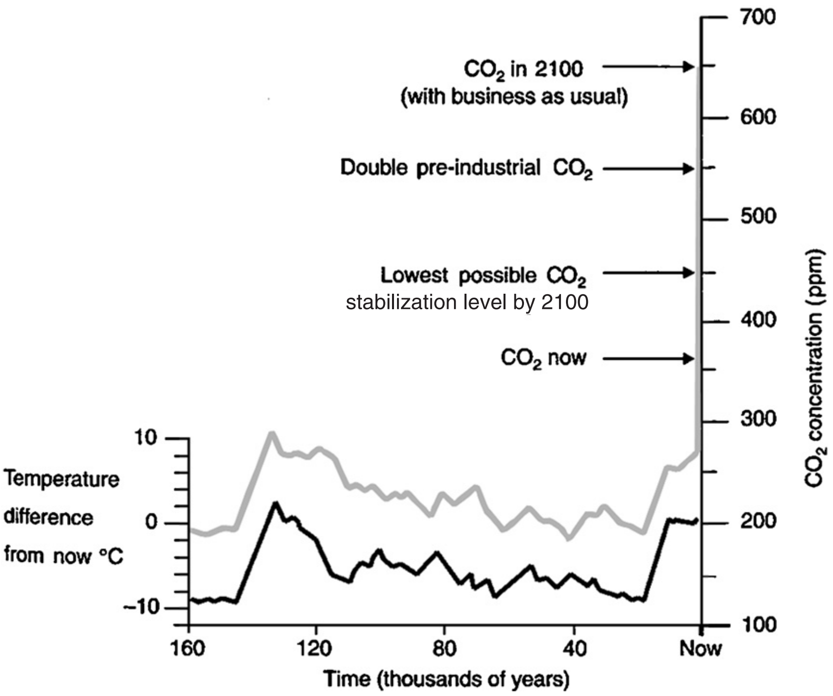

Figure 8. Variations over the last 160 000 years of polar temperature and atmospheric CO_2 concentrations derived from data from the Vostok ice core from Antarctica [16]. It is estimated that the variation of global average temperature is about half that in the polar regions. Also shown is the current CO_2 concentration of about 377 ppm and the likely rise during the 21st century under various projections of its growth.

have, for instance, with changes in ocean circulation. Not surprisingly, questions are being asked about the stability of future climate and whether such rapid changes may occur again (see section 7).

Data from the deepest ice cores can take us back over 700 000 years including eight ice age cycles during which the correlations between temperature and CO_2 concentrations shown in figure 8 are repeated [17]. To go further back, over the past million years, the composition of ocean sediments can yield information. Fossils of plankton and other small sea creatures deposited in these sediments also contain the two main isotopes of oxygen. The ratio of their abundances is sensitive both to the temperature and to the total volume of ice in the world's ice caps at the time of the fossils' formation.

From the variety of paleoclimate data that is available, variations in the volume of ice in the ice-caps can be reconstructed over the greater part of the last million years (figure 9(*c*)). In this record six or seven major ice ages, at intervals of approximately 100 000 years, can be identified.

The most obvious place to look for the cause of regular cycles in climate is outside the Earth, in the sun's radiation. Three regular variations occur in the orbit of the Earth around the sun (figure 9(*a*)) in its eccentricity with a period of about 100 000 years, in the tilt of the Earth's axis (currently 23.5°) with a period of about 41 000 years and in the longitude of perihelion (currently in January) that moves through the months of the year with a period of about 23 000 years.

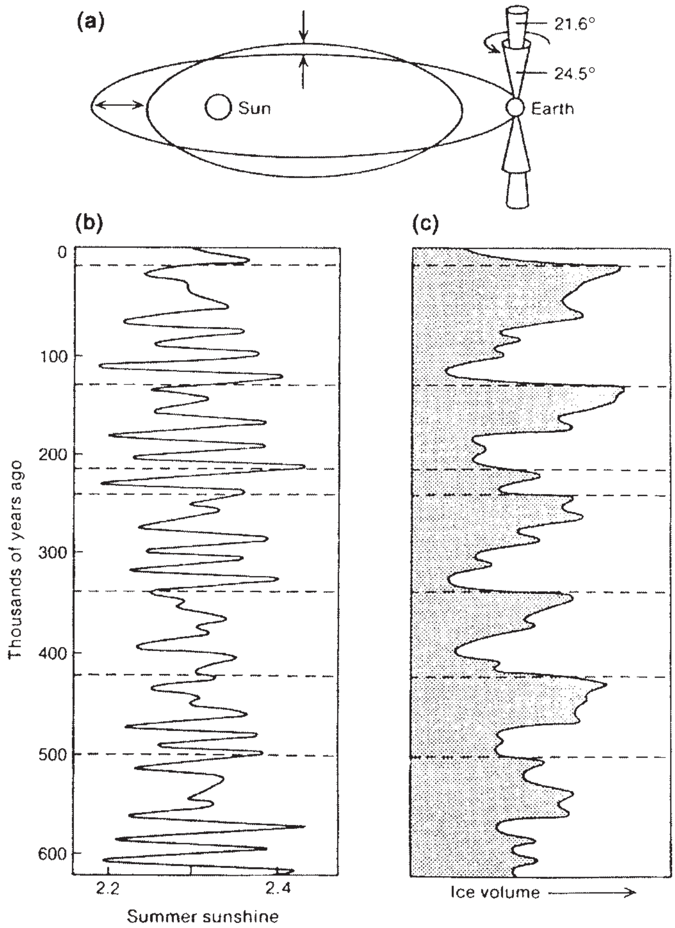

Figure 9. Variations in the Earth's orbit (*a*), in its eccentricity, the orientation of its spin axis (between 21.6° and 24.5°) and the longitude of perihelion (i.e. the time of year when the Earth is closest to the sun), cause changes in the average amount of summer sunshine (in millions of joules per square metre per day) near the poles (*b*). These changes appear as cycles in the climate record in terms of the volume of ice in the ice caps (*c*) [18].

As these changes occur, although the total quantity of solar radiation reaching the Earth varies little, the distribution of that radiation with latitude and season over the Earth's surface changes considerably. The changes are especially large in polar regions where the variations in summer sunshine, for instance, reach about 10% (figure 9(*b*)). James Croll, a British scientist, first pointed out in 1867 that the major ice ages of the past might be linked with these regular variations. His ideas were developed in 1920 by Milutin Milankovitch, a climatologist from Yugoslavia, whose name is usually linked with the theory. Inspection by eye of the relationship between the variations of polar summer sunshine and global ice volume shown in figure 9 suggests a significant connection. Careful study of the correlation between the two curves confirms this and demonstrates that 60% of the variance in the climatic record of global ice volume falls close to the three frequencies of regular variations in the Earth's orbit, thus providing support for the Milankovitch theory.

More careful study of the relationship between ice ages and the Earth's orbital variations shows that the size of the climate changes is larger than might be expected from forcing

by solar radiation changes alone. To explain the climate variations, positive feedback processes need to be introduced, for instance that of CO_2 changes influencing atmospheric temperature through the greenhouse effect, illustrated by the strong correlation between average atmospheric temperature and CO_2 concentration (figure 8). Such a correlation does not, of course, prove the existence of the greenhouse feedback; in fact, part of the correlation arises because the atmospheric CO_2 concentration is itself influenced, through biological feedbacks (see section 4), by factors related to the average global temperature. However, climates of the past cannot be modelled successfully without taking the greenhouse feedback into account [19].

An obvious question to ask is when, on the Milankovitch theory, is the next ice age due? We are currently in a period of relatively small solar radiation variations and the best projections for the long term are of a longer than normal interglacial period leading to the beginning of a new ice age perhaps in 50 000 years' time [20].

4. Greenhouse gases

4.1. Carbon dioxide

In figure 3 emissions from the main greenhouse gases were identified in the infrared spectrum. As was mentioned in section 2, water vapour provides the largest contribution to the natural greenhouse effect [21]. But, the most important gas that is increasing in the atmosphere because of human activities is carbon dioxide. If, for the moment, we ignore the effects of the CFCs and changes in ozone, which vary considerably over the globe and which are therefore more difficult to quantify, the increase in carbon dioxide (CO_2) has contributed about 70% of the enhanced greenhouse effect to date, methane (CH_4) about 24% and nitrous oxide (N_2O) about 6% (figure 13).

CO_2 provides the dominant means through which carbon is transferred in nature between a number of natural carbon reservoirs (the atmosphere, oceans and the land biosphere)—a process known as the carbon cycle (figure 10). About one-fifth of the total CO_2 in the atmosphere is cycled in and out each year, part with the land biota (e.g. through respiration and photosynthesis) and part through physical and chemical processes across the ocean surface. The land and ocean reservoirs are much larger than the amount in the atmosphere; small changes in these larger reservoirs could, therefore, have a large effect on the atmospheric concentration.

On the timescales with which we are concerned anthropogenic carbon emitted into the atmosphere as CO_2 is not destroyed but redistributed among the different carbon reservoirs on a wide range of timescales that range from less than a year to decades (for exchange with the top layers of the ocean and the land biosphere) to millennia (for exchange with the deep ocean or long-lived soil pools). These timescales are generally much longer than the average time of about 5 years that a particular CO_2 molecule spends in the atmosphere. The large range of turnover times means that the time taken for a perturbation in the atmospheric CO_2 concentration to relax back to an equilibrium cannot be described by a single time constant. Although about a hundred years is often quoted so as to provide some guide, the use of a single lifetime can be very misleading.

Before human activities became a significant disturbance, and over periods short compared with geological timescales, the exchanges between the reservoirs were remarkably constant. For several thousand years before the beginning of industrialization around 1750, a steady balance was maintained, such that the mixing ratio (or mole fraction) of CO_2 in the atmosphere as measured from ice cores (see section 3) kept within about 10 ppm (parts per million) of a mean value of about 280 ppm.

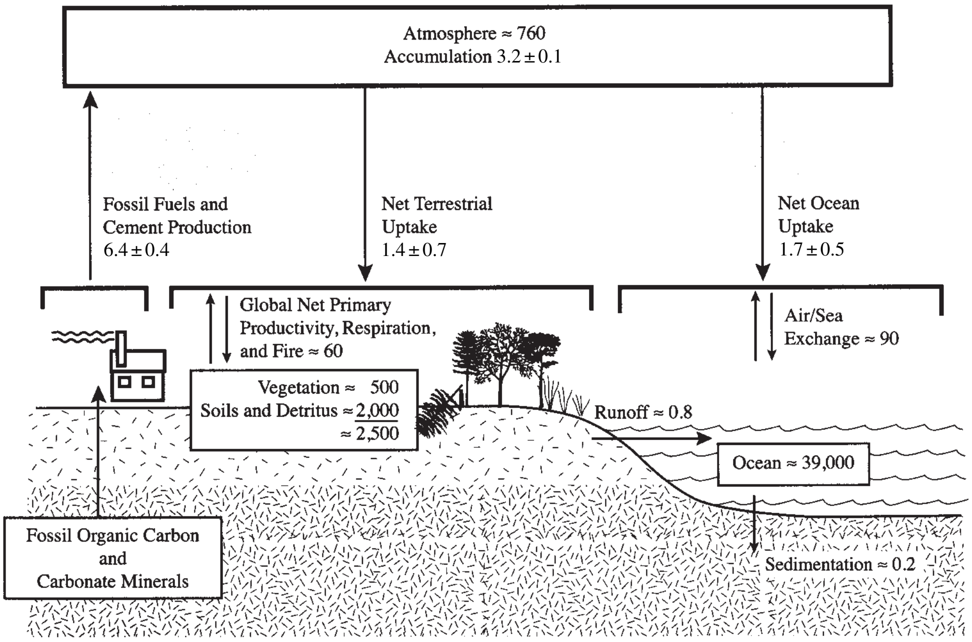

Figure 10. The global carbon cycle, showing the carbon stocks in reservoirs (in GtC) and carbon flows (in Gt/year) relevant to the anthropogenic perturbation as annual averages over the decade from 1989 to 1998 [22]. The units are thousand millions of tonnes or gigatonnes (Gt).

The Industrial Revolution disturbed this balance and, since it began, approximately 600 thousand million tonnes (or gigatonnes, Gt) of carbon have been emitted into the atmosphere from fossil fuel burning—providing the main cause of the increase of over 30% in CO_2 concentration—from 280 to about 377 ppm at the present day (figure 11(*a*)). Accurate measurements since 1959 from an observatory near the summit of Mauna Loa in Hawaii show that CO_2 is currently increasing on average each year by about 1.5 ppm although there are large variations from year to year (figure 11(*b*))—adding each year about 3.3 Gt to the atmospheric carbon reservoir.

In table 1 are shown for the 1980s and 1990s the average annual emissions of CO_2 from fossil fuel burning and from cement manufacture. Another anthropogenic source of CO_2 is from land use change, in particular from deforestation through logging or burning especially in tropical regions, balanced in part by aforestation or forest re-growth mostly at higher latitudes. This contribution is harder to quantify but some estimates are given in the table. For the 1980s, annual anthropogenic emissions from all sources amounted to about 7.1 Gt, over three quarters from fossil fuel burning. About 45% of these remained to provide the annual increase of about 3.3 Gt in the atmospheric concentration. The other 55% was taken up between the other two reservoirs: the oceans and the land biota. Figure 12 shows that these fractions may change substantially in the future.

The exchange of CO_2 between atmosphere and ocean (about 90 Gt per year is so exchanged—figure 10) establishes an equilibrium between the concentration of CO_2 dissolved in the surface waters and that in the air above the surface. The chemical laws governing this equilibrium are such that if the atmospheric concentration changes by 10% the concentration in solution in the water changes by only one tenth of this: 1%. This change will occur in the upper waters of the ocean, the top hundred metres or so, thus enabling part of the anthropogenic

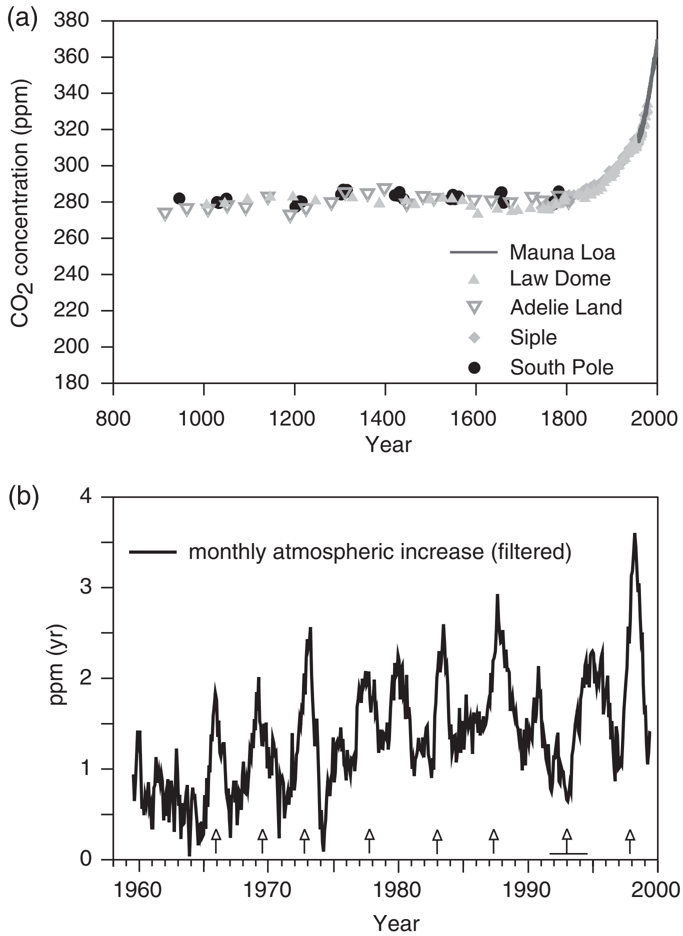

Figure 11. Atmospheric carbon dioxide concentration [23], (*a*) from Antarctic ice cores for the past millennium; recent atmospheric measurements from the Mauna Loa observatory in Hawaii are also shown; (*b*) monthly changes in atmospheric carbon dioxide concentration, filtered so as to remove seasonal cycle; vertical arrows denote El Niño events; note the small rate of growth from 1991 to 1994, which may be connected with events such as the Pinatubo volcanic eruption in 1991 or the unusual extended El Niño of 1991–1994 (denoted by horizontal line). Figure 11(*b*) has been updated to 2003 by Chris Jones of the Hadley Centre, UK.

carbon dioxide added to the atmosphere (most of the ocean's share of the 55% mentioned above) to be taken up quite rapidly. Absorption in the ocean's lower levels takes longer; mixing of surface water with water at lower levels takes up to several hundred years or, for the deep ocean, over a thousand years. This process whereby carbon dioxide is gradually drawn from the atmosphere to the ocean's lower levels is known as the *solubility pump*.

Biological activity in the oceans also plays an important role. As plant and animal plankton die and decay some of the carbon they contain is carried downwards into lower levels of the ocean adding to the carbon content of those levels. Some is carried to the very deep water or to the ocean bottom where, so far as the carbon cycle is concerned, it is out of circulation for hundreds or thousands of years. This process, whose contribution to the carbon cycle is known as the *biological pump,* has been important in determining the changes of carbon dioxide concentration in both the atmosphere and the ocean during the ice ages (figure 8).

Table 1. Components of the annual average global carbon budget for the 1980s and 1990s—in Gt of carbon per year [24] (positive values are fluxes to the atmosphere, negative values represent uptake from the atmosphere).

	1980s	1990s[a]
Emissions (fossil-fuel, cement)	5.4 ± 0.3	6.4 ± 0.4
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1
Ocean–atmosphere flux	-1.9 ± 0.6	-1.7 ± 0.5
Land–atmosphere flux*	-0.2 ± 0.7	-1.4 ± 0.7
*Partitioned as follows		
Land-use change	1.7 (0.6 to 2.5)	1.4 to 3.0
Residual terrestrial sink	−1.9 (−3.8 to 0.3)	−4.8 to −1.6

[a] The larger negative figures for land–atmosphere flux and for residual terrestrial sink in the 1990s are probably at least partially due to the influence of the Pinatubo volcano.

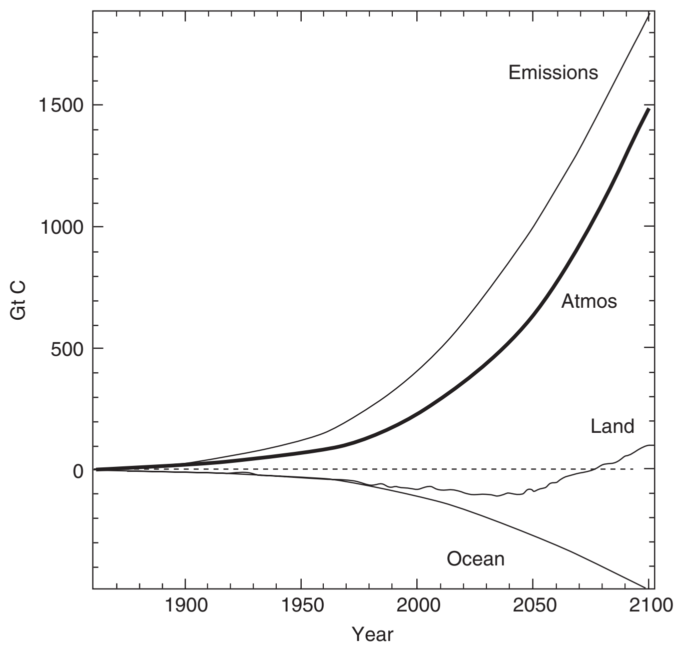

Figure 12. Illustrating the possible effects of climate feedbacks on the carbon cycle [29]. Results are shown of the changing budgets of carbon (in gigatonnes of carbon) in the atmosphere, land and ocean in an ocean–atmosphere model coupled to an ocean carbon cycle model (that includes the transfer of carbon dioxide to depth through both the solubility pump and the biological pump) and a dynamic global vegetation model (that includes the exchange of carbon with the soil and with five different types of plants). The model was run with the fossil fuel carbon dioxide emissions from 1860 to the present and then projected to 2100 assuming the IS 92a scenario shown in figure 18. Note that because of climate feedbacks, the terrestrial biosphere changes from being a net sink of carbon to being a net source around the middle of the 21st century. Note also as this source becomes stronger, by 2100 the atmospheric carbon content is increasing at about the same rate as the total emissions (i.e. the ‘airborne fraction’, or the fraction of fossil fuel emissions that remains in the atmosphere, has changed from being about a half in the year 2000 to being about unity in 2100). Note also that an atmospheric carbon content of 1500 Gt more than it was in 1860 is equivalent to a concentration of nearly 1000 ppm.

Information regarding partitioning of anthropogenic emissions between atmosphere, land biosphere and ocean (as in table 1) can be obtained from a number of sources [25] for instance, from inverse modelling studies of the detailed distribution of atmospheric CO_2 concentration, from observations of the seasonal cycle of atmospheric CO_2 concentration and its difference between the hemispheres (more CO_2 is removed from the atmosphere during the northern hemisphere growing season, some of which is returned as vegetation dies away in the winter), from observations of the relative abundance of the different carbon isotopes, or from comparing trends in atmospheric CO_2 concentration with very accurate observations of trends in the oxygen–nitrogen ratio. This latter provides information because, from the CO_2 taken up on land, the oxygen is returned to the atmosphere while when CO_2 is dissolved in the ocean, both carbon and oxygen are removed.

The global land–atmosphere flux in table 1 represents the balance of a net flux due to land-use changes that has generally been positive (i.e. a source of carbon to the atmosphere) and a residual component that is, by inference, a negative flux or carbon sink. The main processes that contribute to the residual carbon sink are believed to be the CO_2 'fertilization' effect (increased CO_2 in the atmosphere leads to increased growth in some plants) and the effects of increased use of nitrogen fertilizer. The magnitudes of these contributions (table 1) are difficult to estimate directly and are subject to much more uncertainty than their total, which can be inferred from the requirement to balance the overall carbon cycle budget.

The CO_2 fertilization effect is an example of a biological feedback process that is negative. Positive feedback processes, that tend to add to the anthropogenic increase also exist; in fact, the positive processes are potentially stronger than the negative ones. One such positive feedback is the effect of higher temperatures on respiration, especially through microbes in soils, leading to increased CO_2 emissions. Studies of the variations of atmospheric carbon dioxide during El Niño events and following the Pinatubo volcanic eruption in 1991 indicate a relation such that a change of 5˚C in average temperature leads to a 40% change in global average respiration rate [26]—a substantial effect. A question that needs to be resolved is whether this relation still holds over longer-term changes of the order of several decades to a century [27].

A further positive feedback is the reduction of growth or the die-back especially in forests because of the stress caused by climate change—this may be particularly severe in Amazonia [28]. A number of carbon cycle models show that, through these two effects during the second half of the 21st century, the residual terrestrial sink (table 1) could change sign and become a substantial net source (figure 12 and see also section 7).

4.2. Methane

Methane is the main component of natural gas. Its common name used to be marsh gas because it can be seen bubbling up from marshy areas where organic material is decomposing. Data from ice cores show that for at least two thousand years before 1800 its concentration in the atmosphere was about 0.7 ppm. Since then its concentration has more than doubled. During the 1980s it was increasing at about 10 ppb/yr but during the 1990s the average rate of increase fell to around 5 ppb/yr [3]. Although the concentration of methane in the atmosphere is much less than that of CO_2 (less than 2 ppm compared with about 370 ppm for carbon dioxide), its greenhouse effect is far from negligible. That is because the enhanced

[3] In 1992, the increase slowed to almost zero. The reason for this is not known but one suggestion is that, because of the collapse of the Russian economy, the leakage from Siberian natural gas pipelines was much reduced.

greenhouse effect caused by a molecule of methane is about 8 times that of a molecule of CO_2 [30][4].

The main natural source of methane is from wetlands [31]. A variety of other sources result directly or indirectly from human activities, for instance from leakage from natural gas pipelines and oil wells, rice paddy fields, enteric fermentation (belching) from cattle and other livestock, decay of rubbish in landfill sites and from wood and peat burning. Large uncertainty exists in estimating the size of many of these sources, although measurements of the proportions of different carbon isotopes in atmospheric methane assist in estimating the proportion from fossil fuel sources.

The main process for methane removal from the atmosphere is through chemical destruction. It reacts with hydroxyl (OH) radicals that are present in the atmosphere because of processes involving sunlight, oxygen, ozone and water vapour. The average lifetime of methane in the atmosphere is determined by the rate of this loss process. At about 12 years [32], it is much shorter than the lifetime of CO_2. Because of the critical role of OH, the concentration of methane and its lifetime are partially controlled by the presence of pollutants such as the oxides of nitrogen that, therefore, possess an indirect influence on the amount of global warming (see section 5). It is of course important to take these indirect effects into account, but it is also important to recognize that their contribution is much less than the direct effect of the major contributors to human-generated greenhouse warming, namely CO_2 and methane.

4.3. Nitrous oxide

Nitrous oxide is another minor greenhouse gas. Its concentration in the atmosphere of about 0.3 ppm is rising at about 0.25%/yr and is about 16% greater than in pre-industrial times. The largest emissions to the atmosphere are associated with natural and agricultural ecosystems; those linked with human activities are probably due to increasing fertilizer use. Biomass burning and the chemical industry (e.g. nylon production) also play some part. The sink of nitrous oxide is photodissociation in the stratosphere and reaction with electronically excited oxygen atoms, leading to an atmospheric lifetime of about 120 years.

4.4. CFCs and ozone

The CFCs are man-made chemicals which appear to be ideal for use in refrigerators, the manufacture of insulation and aerosol spray cans. Since they are so chemically inert, once they are released into the atmosphere they remain for a long time—one or two hundred years—before being destroyed. Their use increased rapidly through the 1980s giving them a concentration in the atmosphere (adding together all the different CFCs) of about 1 ppb that is causing two serious environmental problems. The first is that they destroy ozone (O_3) [33], an extremely reactive gas present in small quantities in the stratosphere (a region of the atmosphere between about 10 and 50 km in altitude) where it absorbs solar ultraviolet radiation—radiation that would otherwise be harmful to us and to other forms of life at the Earth's surface. CFC molecules that reach the stratosphere are also dissociated by the action of ultraviolet sunlight, the resulting chlorine atoms readily reacting with ozone destroying it through a catalytic cycle.

[4] The GWP is also often expressed as the ratio of the effect for unit mass of each gas in which case the GWP for methane (whose molecular mass is 0.36 of that of carbon dioxide) becomes about 23 for the 100 year time horizon. About 75% of the contribution of methane to the greenhouse effect is because of its direct effect on the outgoing thermal radiation. The other 25% arises because of its influence on the overall chemistry of the atmosphere. Increased methane eventually results in small increases in water vapour in the upper atmosphere, in tropospheric ozone and in carbon dioxide, all of which in turn add to the greenhouse effect.

Because of this problem of ozone depletion, international action was taken through the Montreal Protocol of 1987 to phase out the production of CFCs. As a result, the concentration of CFCs in the atmosphere is no longer increasing. However, since they possess a long life in the atmosphere, little decrease will be seen for some time and significant quantities will be present well over a hundred years from now.

What particularly concerns us here is that both CFCs and ozone are greenhouse gases [34]. They possess absorption bands in the region known as the longwave atmospheric window (see figure 3) where few other gases absorb. Since a CFC molecule added to the atmosphere has a greenhouse effect five to ten thousand times greater than an added molecule of CO_2, despite their very small concentration they have a significant greenhouse effect (see section 5).

The effect on global warming of ozone depletion depends critically on the height in the atmosphere at which it is being destroyed. Further, ozone depletion is concentrated at high latitudes while the greenhouse effect of the CFCs is uniformly spread over the globe. In tropical regions there is virtually no ozone depletion so no change in the ozone greenhouse effect. At mid-latitudes, very approximately, the greenhouse effects of ozone reduction and of the CFCs compensate for each other. In polar regions the reduction in the greenhouse effect of ozone more than compensates for that of the CFCs [35].

As CFCs are phased out, they are being replaced to some degree by other halocarbons, for instance by hydrofluorocarbons (HFCs) that contain no chlorine or bromine, do not destroy ozone and are not covered by the Montreal Protocol. Because of their shorter lifetime, typically tens rather than hundreds of years, their contribution to global warming for a given rate of emission, will be less than for the CFCs. However, since their rate of manufacture could increase substantially their potential contribution to greenhouse warming is being considered together with that from some other related compounds (e.g. CF_4, C_2F_6 and SF_6) that possess very long atmospheric lifetimes, probably more than 1000 years, and that are produced in some industrial processes.

Ozone is also present in the lower atmosphere or troposphere, some of it being transferred downwards from the stratosphere and some generated locally by chemical action, particularly as a result of the action of sunlight on the oxides of nitrogen. It is especially noticeable in polluted atmospheres near the surface. Significant amounts may also be created in the upper troposphere as a result of the nitrogen oxides emitted from aircraft exhausts. In the northern hemisphere, both observations and model simulations of the relevant chemical processes suggest that ozone concentrations in the troposphere have doubled since pre-industrial times.

5. Radiative forcing

5.1. What is radiative forcing?

Radiative forcing (introduced in section 2.1) is defined as the change in average net radiation at the top of the troposphere[5] that occurs because of a change in the concentration of a greenhouse gas or some other constituent or because of some other change in the climate system. The response of the climate to radiative forcing leads to a restoration of the radiative balance between incoming and outgoing radiation. Through the concept of radiative forcing, the relative greenhouse effects of different atmospheric constituents can be compared as can forcings that might arise from other changes in the system. Before addressing this comparison, two sources of radiative forcing other than greenhouse gases will be briefly described.

[5] By defining radiative forcing as the radiative imbalance at the top of the troposphere rather than at the top of the atmosphere avoids the complication of dealing with the effect of the stratosphere.

5.2. Particles in the atmosphere [36]

Small particles suspended in the atmosphere (often known as *aerosols*) affect its energy balance because they both absorb radiation from the sun and scatter it back to space. We can easily see the effect of this on a bright day in the summer with a light wind when downwind of an industrial area. Although no cloud appears to be present, the sun appears hazy—it is called 'industrial haze'. Under these conditions a significant proportion of incident sunlight is being lost as it is scattered out of the atmosphere by millions of small particles (typically between 0.001 and 0.01 mm in diameter) in the haze.

Atmospheric particles come from a variety of sources. They arise partially from natural causes; they are blown off the land surface, especially in desert areas; they result from forest fires and they come from sea spray. From time to time volcanoes eject large quantities of particles and gases into the upper atmosphere. Other particles arise from human activities—from biomass burning (e.g. the burning of forests) and the sulfates and soot resulting from the burning of fossil fuels. Sulphate particles are particularly important. They are formed as a result of chemical action on sulfur dioxide, a gas that is produced in large quantities by power stations and other industries in which coal and oil (both of which contain sulfur in varying quantities) are burnt. Because these particles remain in the atmosphere only for about five days on average, their effect is mainly confined to regions near the sources of the particles, i.e. the major industrial regions of the northern hemisphere. Over limited regions of the northern hemisphere the radiative effect of these particles is comparable in size, although opposite in effect, to that of human-generated greenhouse gases up to the present time.

The influence of black soot from biomass and fossil fuel burning on radiative forcing in the atmosphere has also recently been emphasized [37]. Black soot is also present on the snow or ice surfaces in the Arctic or other areas of the northern hemisphere, where it affects albedo and therefore introduces a small but not insignificant radiative forcing [38].

In addition to this *direct* effect of aerosol, a further way by which particles in the atmosphere influence the climate is through their effect on cloud formation. Two mechanisms of this *indirect* forcing have been proposed. The first is the influence of the number of particles and their size on cloud radiative properties. If particles are present in large numbers when clouds are forming, the resulting cloud consists of a large number of smaller drops, smaller than would otherwise be the case. Polluted fogs in cities are formed in this way. Such a cloud is more highly reflecting to sunlight than one consisting of larger particles, thus further increasing the energy loss resulting from the presence of the particles. The second mechanism arises because of the influence of droplet size and number on precipitation efficiency and the life time of clouds and hence on the geographic extent of cloudiness. Observational evidence exists for both of these mechanisms but the processes involved are difficult to model and vary a great deal with the particular situation. Estimates of their magnitude (see figure 13) therefore remain very uncertain. To refine these estimates, more studies are needed especially by making careful and comprehensive measurements on suitable clouds.

5.3. Variations in solar radiation

In section 3.4, we described the influence on climate of past changes in the distribution of solar radiation over the Earth due to variations in the geometry of the Earth's orbit. The question is also often raised as to whether the sun's energy output could change with time introducing radiative forcing that could influence the climate. The only accurate direct measurements of solar output that are available are those since 1978, from satellites outside the disturbing effects

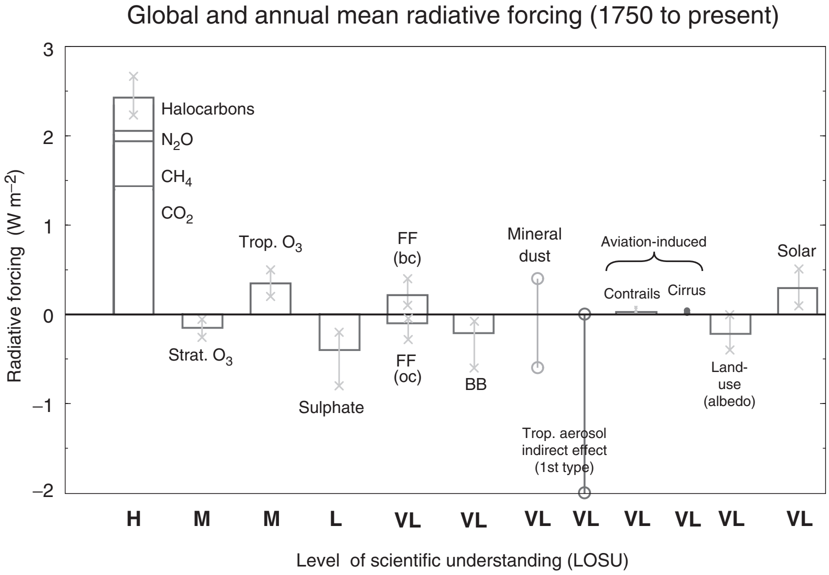

Figure 13. Global, annual mean radiative forcings ($W\,m^{-2}$) due to a number of agents for the period from pre-industrial (1750) to 2000 [41]. The height of the rectangular bar denotes a best estimate value while its absence denotes no best estimate is possible because of large uncertainties. The vertical lines with 'x' or 'o' delimiters indicates estimates of the uncertainty ranges. A 'level of scientific understanding (LOSU)' index is accorded to each forcing, with H, M, L and VL denoting, high, medium, low and very low levels, respectively. This represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the mechanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual contributions shown. The second and third bars apply to stratospheric and tropospheric ozone. The next bars denote the direct effect of aerosols from fossil fuel (FF) burning—separated into black carbon (bc) and organic carbon (oc) components—and from biomass burning (BB). The sign of the effects due to mineral dust is itself an uncertainty. Only the first indirect aerosol effect is estimated, as little quantitative evidence exists regarding the second (see section 5.2). All the forcings have distinct spatial and seasonal variations so that they cannot be added up and viewed *a priori* as providing offsets in terms of complete global climate impact [42].

of the Earth's atmosphere. These measurements indicate a very constant solar output, changing by about 0.1% between maximum and minimum in the cycle of solar activity indicated by the number of sunspots.

It is known from astronomical records and from measurements of radioactive carbon in the atmosphere that this solar sunspot activity has, from time to time over the past few thousand years, shown large variations. Of particular interest is the period known as the Maunder Minimum in the 17th century when very few sunspots were recorded [39]. Studies of the recent measurements of solar output correlated with other indicators of solar activity, when extrapolated to this earlier period, suggest that the sun was a little less bright in the 17th century, perhaps by about 0.4% or about $1\,W\,m^{-2}$ in terms of the average solar energy incident on the Earth's surface. This reduction in solar energy may have been a cause of the cooler period at that time known as the 'Little Ice Age'. Careful studies have estimated that since 1850 the maximum variations in the solar energy incident on the Earth's surface are unlikely to be greater than about $0.5\,W\,m^{-2}$ (figure 13). This is about the same as the change in the

energy regime at the Earth's surface due to ten years' increase in greenhouse gases at the current rate.

In the above, the effects of changes in the total solar energy have been considered. It is also possible that climate could be affected through changes in the spectrum of solar radiation. For instance, changes in the ultraviolet can affect the atmospheric ozone distribution that could in turn influence the climate. However, insufficient evidence exists that this or other similar mechanisms that have been proposed (e.g. through changes in solar cosmic rays) are leading to significant climate change [40].

5.4. Estimates of radiative forcing (1750–2000)

From the information in section 3 regarding the changes in the concentrations of greenhouse gases in the atmosphere and from knowledge of the detailed characteristics of the absorption of these gases in the infrared, their radiative forcing can be calculated. In figure 13 are brought together estimates of global average radiative forcing for the period from 1750 to 2000 for the different greenhouse gases, for tropospheric aerosols of different origins and for changes in solar radiation.

Two other contributions to radiative forcing are included in figure 13. The first is due to changes in the albedo of the surface arising from land-use changes. The second is due to changes in high cloud cover that arise from emissions of water vapour from aircraft. Many examples exist of extensive contrail formation over regions where many aircraft flights regularly occur. Aircraft may also influence cirrus cloud formation through the effect of the particles in aircraft emissions. The overall greenhouse effect of aircraft has been estimated as up to the equivalent of two or three times the effect of their CO_2 emissions [43].

It is useful to be able to compare the radiative forcing generated by different greenhouse gases. Because of their different life times, the future profile of radiative forcing due to releases of greenhouse gases varies from gas to gas. An index called the Global Warming Potential (GWP) has been defined that compares the time-integrated radiative forcing from the instantaneous release of 1 kg of a given gas to that from the release of 1 kg of CO_2. A time horizon also needs to be specified for the period over which the integration is carried out. Applying the GWPs to the emissions from a mixture of greenhouse gases enables the mixture to be considered in terms of an equivalent amount of CO_2. However, because GWPs for different time horizons are very different, they are of limited application and must be used with care.

6. Modelling the climate

6.1. The climate system

So far, our representation of the atmosphere has been of a vertical column representing the global atmosphere—a simple one-dimensional model. This has provided a crude but useful indication of the overall response so far as global average temperature change is concerned. However, to calculate the response in more detail and to describe the likely impacts of climate change, it is necessary to address the patterns of change in the horizontal and also to take account of the influence of all components of the climate system (figure 14) including the oceans and the cryosphere (i.e. the snow and ice). Large variations in space and time exist for the various components of the Earth's radiation budget shown in figure 2 and also for the large amounts of energy that are transported from equatorial to polar regions and across lines of longitude both by the atmosphere and the oceans [44]. The primary tool to describe the

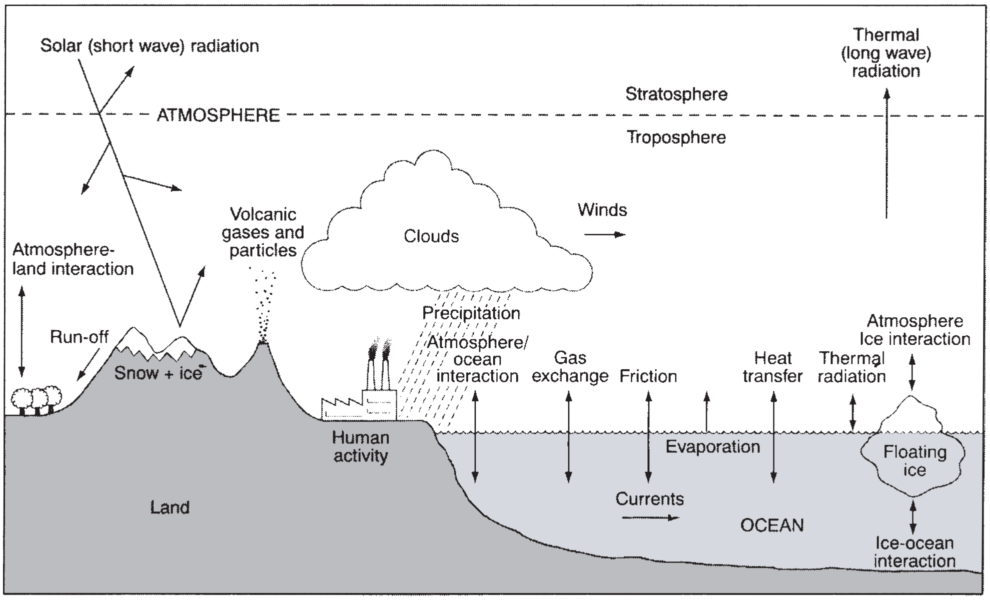

Figure 14. Schematic of the climate system and its components.

detailed climate response to changes in forcing is the numerical model of climate that includes algorithmic descriptions of dynamical and physical processes and interactions between all components of the climate system. As changes are made in the factors that force the climate, the evolution of climate is calculated by integrating the appropriate equations as a function of time.

The technique of numerical weather prediction was first established nearly ninety years ago by an English mathematician, Lewis Fry Richardson [45] who made the first numerical weather forecast during his spare moments while working for the Friends' Ambulance Unit in France during the First World War. But he was many years before his time! It was not until some forty years later that, essentially using Richardson's methods, the first operational weather forecast was produced on an electronic computer. Computers more than one hundred million times faster than the one used for that first operational forecast now run numerical models that provide the basis of all weather forecasts. Early climate models were relatively simple extensions of these atmospheric models to which a 'slab' ocean was added some 50 or 100 m deep, the approximate depth of the 'mixed layer' of ocean that responds to the seasonal heating and cooling at the Earth's surface. Ocean transports were introduced from empirical data. Such models played an important part in model development but were of limited value in predicting climate changes.

The atmosphere and ocean are strongly coupled together. Wind stress at the ocean surface is the main driver for the ocean's circulation and the input of water vapour into the atmosphere through its latent heat release as it condenses is the main energy source of the atmosphere's circulation. Full climate models, therefore, couple the atmospheric and ocean circulations (they are known as AOGCMs—atmosphere–ocean general circulation models) taking particular care that exchanges at the ocean surface of heat, momentum and water are adequately described (figure 15). In addition, a full climate model needs to follow changes in the ice and land surface and fully describe interactions between all the components illustrated in figure 14.

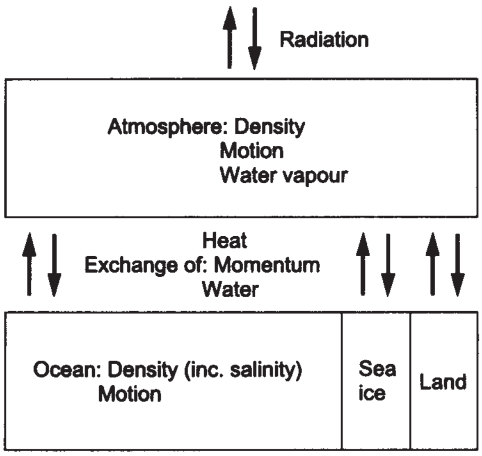

Figure 15. Component elements and parameters of a coupled atmosphere–ocean model including the exchanges at the atmosphere–ocean interface.

6.2. Formulation of a numerical climate model

Numerical models of the weather and the climate are based on the fundamental mathematical equations that describe the physics and dynamics of the movements and processes taking place in the atmosphere, the ocean, the ice and on the land surface [46]. Although they include empirical information, they are not based to any large degree on empirical relationships—unlike numerical models of many other systems, for instance in the social sciences. Most physical processes in the model are parametrized, that is, they are described in terms of algorithms (a process of step-by-step calculation) involving simple variables.

The variables (e.g. pressure, temperature, velocity, humidity (for the atmosphere), salinity (for the ocean, etc) that are needed to describe the dynamics and physics are specified at a grid of points covering the globe. Typical spacing between points is 100–300 km in the horizontal for the atmosphere. For the ocean, because dynamical systems (e.g. large-scale eddies) are smaller in scale, grid point separation is typically about half that in the atmosphere. For both atmosphere and ocean, spacing in the vertical provides around 20 levels. The fineness of the spacing is limited by the power of the computers currently available.

The basic dynamical equations are

- The momentum equations from Newton's second law of motion (when applied to fluids these are known as the Navier–Stokes equations). The horizontal acceleration of a volume of fluid is balanced by the horizontal pressure gradient and the friction. Because the Earth is rotating, the acceleration includes the Coriolis acceleration. The 'friction' in the model mainly arises from motions smaller than the model's grid spacing that are parametrized.
- The hydrostatic equation. The pressure at a point is given by the mass of fluid above that point. Vertical accelerations are neglected.
- The continuity equation. This ensures conservation of mass.
- The thermodynamic equation (the law of conservation of energy).
- The equation of state that relates fluid density to pressure, temperature, salinity (for the ocean) and water vapour (for the atmosphere).

In addition, a number of physical processes in the atmosphere or at the surface need to be included through appropriate parametrizations, namely:

- Moist processes (such as evaporation, condensation, formation and dispersal of clouds).
- Absorption, emission and reflection of solar radiation and thermal radiation.
- Convective processes that occur on scales smaller than the grid spacing.
- Changes in the state of the underlying surface—sea ice or land (e.g. vegetation cover, albedo and roughness)
- Exchanges of momentum (i.e. friction), heat and water (as vapour or liquid) at the ocean–atmosphere interface or at the land surface.

Most of the equations in the model are differential equations. If the rate of change of a quantity, such as fluid velocity, and its value at a given time are known, then its value at a later time can be calculated by integration of the appropriate equations. Hence, the model's predictive powers. In general, the model is employed to investigate *changes* in climate. Integrations can be carried out starting from an initial state generally specified from observations.

The value of numerical climate models is their ability to add together the effects of a very large number of dynamical and physical processes. Because these processes are all non-linear in character, analytical methods are very limited in their capability to describe the complications of the patterns of climate change on a global scale.

6.3. Feedbacks in the climate system

Feedbacks in the climate system, both positive and negative, were mentioned in section 2. To elucidate these feedbacks correctly is one of the most important tasks of climate models. The following four, that are implicit within the model formulations as described, are the most important.

Water vapour feedback [47]. With a warmer atmosphere more evaporation occurs from the ocean and from wet land surfaces. On average, therefore, a warmer atmosphere will possess a higher water vapour content. Since water vapour is a powerful greenhouse gas, on average a positive feedback results, of a magnitude that is estimated approximately to double the increase in the global average temperature that would arise with fixed water vapour [48].

Cloud-radiation feedback. This is more complicated as several processes are involved. Clouds interfere with the transfer of radiation in the atmosphere in two ways (figure 16). First, they reflect a certain proportion of solar radiation back to space, so reducing the total energy available to the system. Second, they absorb thermal radiation emitted by the Earth's surface so blanketing the surface in a similar way to greenhouse gases.

Which effect dominates for any particular cloud depends on the cloud temperature (and hence on the cloud height) and on its detailed optical properties (e.g. its reflectivity to solar radiation and its interaction with thermal radiation). The latter depends on its thickness, whether the cloud is of water or ice, its liquid or solid water content and the average size of the cloud particles. In general, for low clouds the reflectivity effect wins; for high clouds, by contrast, the blanketing effect is dominant. The overall feedback effect of clouds, therefore, can be either positive or negative. Climate is very sensitive to possible changes in cloud amount or structure, as can be seen from the results of models discussed in later sections. To illustrate this, table 2 shows that the hypothetical effect on the climate, of changes of a few per cent in cloud cover is comparable with the expected changes due to a doubling of the carbon dioxide

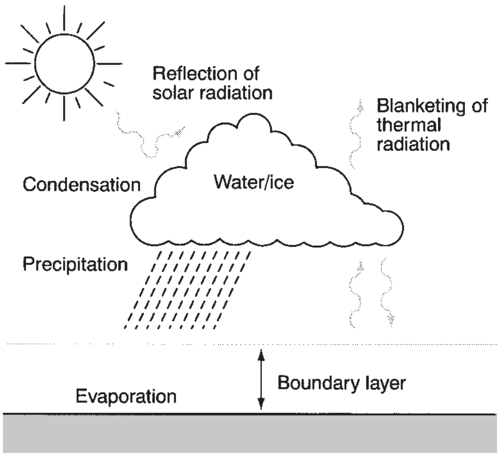

Figure 16. Schematic of the physical processes associated with clouds.

Table 2. Estimates of global average temperature changes under different assumptions about changes in greenhouse gases and clouds.

Greenhouse gases	Clouds	Change in °C from current average global surface temperature of ∼15°C
As now	As now	0
None	As now	−32
None	None	−21
As now	None	4
As now	As now but + 3% high cloud	0.3
As now	As now but + 3% low cloud	−1.0
Doubled CO_2 concentration otherwise as now	As now (no additional cloud feedback)	1.2
Doubled CO_2 concentration + best estimate of feedbacks	Cloud feedback included	2.5 (range of uncertainty 1.5–4.5)

concentration. The largest contribution to the range of uncertainty quoted in the last entry in the table is that due to lack of knowledge regarding cloud feedback.

Ocean-circulation feedback [49]. In addition to the strong coupling between atmosphere and oceans that has already been mentioned, oceans act on the climate in two other main ways. First, they possess a large heat capacity compared with the atmosphere—the entire heat capacity of the atmosphere is equivalent to less than 3 m depth of water. The oceans, therefore, tend to warm much more slowly than the atmosphere and exert a dominant control on the rate at which atmospheric changes occur. Second, through their internal circulation they redistribute heat throughout the climate system. The amount of heat transported from the equator to the polar regions by the oceans is substantially smaller than that transported by the atmosphere [50]. However, the regional distribution of that transport is very different; even small changes in that transport could have large implications for climate change. For instance, the amount of heat transported by the north Atlantic Ocean is over 1000 terawatts (10^{15} W) or about 100 times the total amount of commercial energy produced globally. To put it further

in context, in winter, north-west Europe receives more energy from the ocean than from the incoming solar radiation.

Ice-albedo feedback. An ice or snow surface is a powerful reflector of solar radiation (the albedo is a measure of its reflectivity). As some ice melts at the warmer surface, solar radiation, previously reflected back to space by the ice or snow, is absorbed leading to further increased warming. This is another positive feedback that on its own would increase the global average temperature rise due to doubled carbon dioxide by about 20%.

6.4. Model evaluation [51]

An obvious test of a climate model is to run it for a number of years of simulated time and compare in detail the model-generated climate to the current observed climate in both its average and its variability. Models have improved greatly in recent years against such tests. However, it is also necessary to demonstrate the model's ability to accurately simulate changes in climate due to changing climate forcing. This has been done by testing the model's ability to simulate the effects of large perturbations of the climate, for instance such as arise from El Niño events (see section 7.3) or from volcanic eruptions. For instance, climate perturbations resulting from the eruption of Mount Pinatubo in 1991, both in the global average [52] and regionally [53], were well simulated by models. Models have also been tested through comparing data from paleoclimate studies with simulations of past climates when the distribution of incident solar radiation on the Earth was substantially different from that at present (see section 3.3). The increase in available computing power in recent years has enabled comparisons to be made of model runs from different initial conditions (often referred to as ensembles) [54], so exploring model 'natural' variability and prediction uncertainty (see next section). Through these various studies confidence has been built in the value of models to simulate changes of climate that occur because of human activities.

6.5. Climate and chaos

The section on climate modelling began by referring to weather forecasting models. The limit of detailed weather prediction is about 14 days that arises from the 'chaotic' nature of weather [54]—that is its sensitivity to the initial state from which the forecast began, the influence of which, for a chaotic system grows exponentially with time. In fact, it was in studying a simple model of weather in 1963 that Edward Lorenz first recognized chaotic phenomena [55]. The question might be asked if weather prediction breaks down after such a short period, how can we have confidence that realistic predictions can be made of climate, or the average weather, over much longer periods.

In the last section, it was stated that confidence in models arises from their ability to describe current climate and to simulate some of the effect of changes in climate forcing in the past. But is there evidence apart from that of models to support the view that climate is predictable? In section 3.3 we pointed out that the correlation between the Milankovitch cycles in the Earth's orbital parameters and the cycles of climate change (see section 3.3) provides strong evidence to substantiate the Earth's orbital variations as the main factor responsible for triggering large climate changes, such as the ice ages, although the nature of some of the feedbacks still needs to be understood. The existence of this surprising amount of regularity suggests that the climate system is not strongly chaotic so far as these large changes are concerned, but responds in a largely predictable way to Milankovitch forcing. Changes in climate as a result of the increase of greenhouse gases are driven by

changes in the radiative regime at the top of the atmosphere that are not dissimilar in kind (although different in distribution) from the changes that provide Milankovitch forcing. It can be argued, therefore, that the increases in greenhouse gases will also result in a largely predictable response [56].

Despite the successes achieved by climate models, there remain large uncertainties [57]. The estimate of climate sensitivity in the range 1.5˚C to 4.5˚C has not been narrowed over the last twenty years and regional climate change remains poorly predicted. Recent work by Murphy *et al* [58] has explored the dependence of model values of climate sensitivity over a range of 53 different parametrizations of key processes. They found a spread of climate sensitivity from 1.9˚C to 5.3˚C that was only reduced to 2.4˚C to 5.4˚C (5% to 95% range) when they weighted the parametrizations in favour of those that resulted in the best simulations of observed climate. In a more extensive study [59]—an ensemble of over 2000 unique simulations carried out using idle processing capacity on personal computers volunteered by members of the general public—the range of sensitivities varied from just below 2˚C to over 11˚C. The existence of a long tail towards high values in this sensitivity distribution illustrates the importance of further exploration and understanding of different parametrizations and their formulation.

A fundamental problem with numerical models of both weather and climate is that of adequately allowing for the effects of sub-grid-scale motions. For ocean–atmosphere coupled global climate models, limitations of computer power imply that sub-grid-scale means anything smaller than about 100 km. Parametrization schemes typically allow for these motions by simple diffusive-type descriptions that do not allow small-scale motions to influence motions on larger scales. However, turbulence occurs in the atmosphere on all scales. On scales larger than about 10 km, the turbulence is limited by the atmosphere's depth and is essentially two dimensional in character. As Fjortoft [60] first showed, a characteristic of such turbulence is that energy injected into the atmosphere not only cascades to smaller scales but also to larger scales (a reverse cascade) [61]. This has serious implications for the prediction of the influence of anthropogenic climate change on large-scale atmospheric circulation patterns (see section 7.3).

6.6. *Climate of the 20th century*

More than fifteen centres in the world located in ten countries are currently running fully coupled atmosphere–ocean general circulation models. Some of these have been employed to simulate the climate of the last 150 years. An example compared with observed climate is shown in figure 17; similar results have been obtained from many models.

Note from figure 17 that the inclusion of anthropogenic forcings provides a plausible explanation for a substantial part of the observed temperature changes over the last century (especially for the latter part of the century), but that the best match with observations occurs when both natural and anthropogenic factors are included. Assumed changes in solar output and the comparative absence of volcanic activity assist in providing explanations for the increase in global average temperature during the first part of the century. The shorter term variability shown in the model of about a tenth of a degree Celsius arises from internal exchanges in the model between different parts of the climate system, and is not dissimilar to that which appears in the observed record. It has also been possible from comparisons of results from regional models with observations to attribute some of the patterns of regional change to anthropogenic causes [63]. Allen *et al* [64] have used the constraints provided by the observed climate on the simulations of models to quantify the uncertainty in forecasts for the first part of the 21st century.

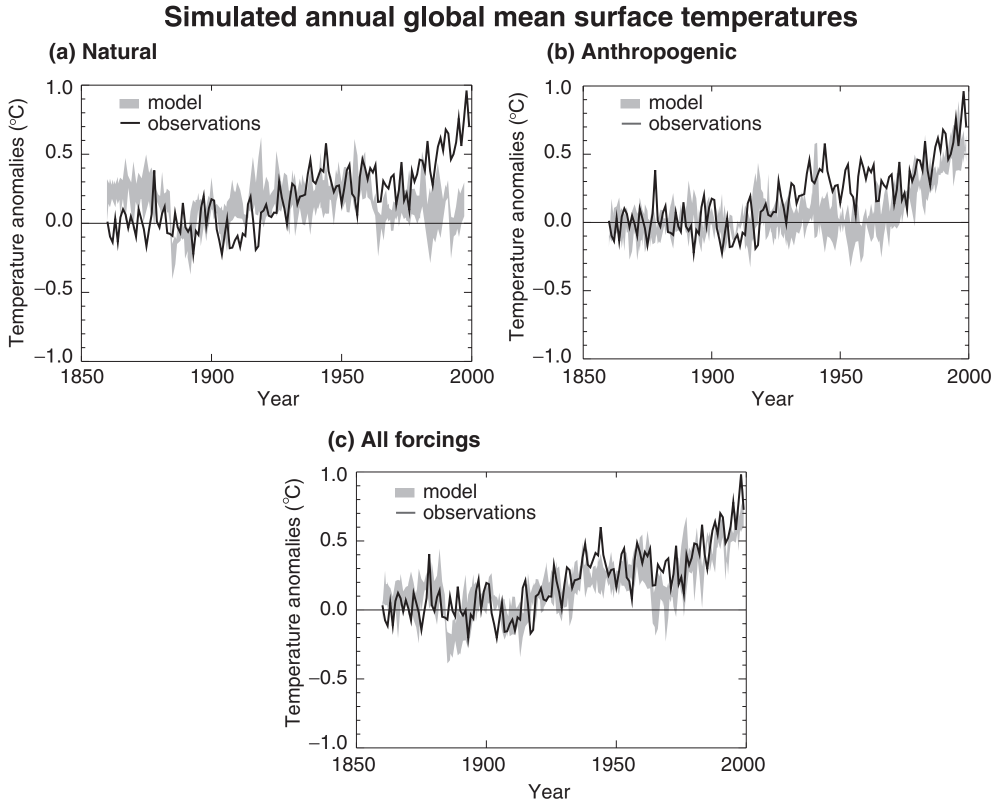

Figure 17. Annual global mean surface temperatures simulated by a climate model compared with observations for the period 1860–2000 [62]. The simulations in (*a*) were done with only natural forcings—solar variation and volcanic activity; in (*b*) with only anthropogenic forcings—greenhouse gases and sulphate aerosols; and in (*c*) with both natural and anthropogenic forcings combined. The simulations are shown in a band that covers the results from four runs with the same model and, therefore, illustrates the scale of natural variability within the model.

Due to the slowing effect of the oceans on climate change, the warming observed or modelled so far is less than would be expected if the climate system were in equilibrium under the amount of radiative forcing due to the current increase in greenhouse gases and aerosols. The increase in ocean heat content over the last 50 years has also been simulated by models showing, when both natural and anthropogenic forcings are included, substantial agreement with observations [65].

Since its formation in 1988 the IPCC has been much involved in the debate as to whether the observed record provides evidence of the influence on the climate of the increase in greenhouse gases. The evidence for both the *detection* and *attribution*[6] of climate change has grown significantly stronger during this period. From studies of the global average temperature increase as in figure 17 and also from studies of patterns of climate change over the globe, the carefully worded conclusion reached in the IPCC 2001 Report [66] is the following: *'In the light of new evidence and taking into account the remaining uncertainties, most of the observed*

[6] Detection is the process of demonstrating that an observed change is significantly different (in a statistical sense) than can be explained by natural variability. Attribution is the process of establishing cause and effect with some defined level of confidence, including the assessment of competing hypotheses.

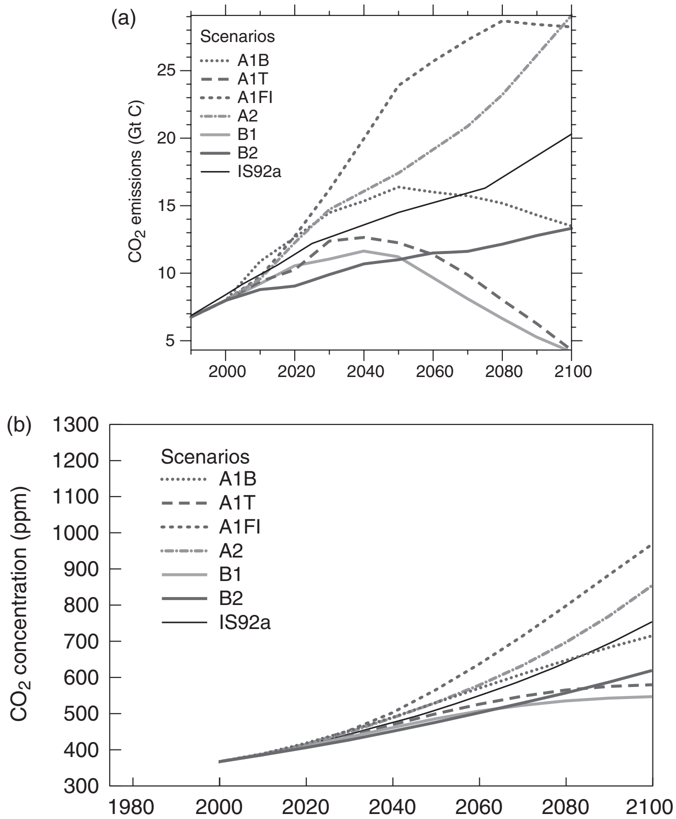

Figure 18. (*a*) Anthropogenic emissions of CO_2 for a representative 6 of the 35 SRES scenarios developed by the IPCC; (*b*) atmospheric CO_2 concentrations resulting from the emissions in (*a*). Also shown is scenario IPCC IS 92a, a 'business-as-usual' scenario published by IPCC in 1992 [68] and widely used. Substantial uncertainties exist in the conversion of emissions to concentrations especially due to possible carbon cycle feedbacks—estimated in 2100 to be from about −10% to +30% (see section 4.1).

warming over the last 50 years is likely[7] *to have been due to the increase in greenhouse gas concentrations.'*

7. The climate of the 21st century and beyond

7.1. Emission scenarios

A starting point for any projections[8] of climate change into the future is a set of descriptions of likely future global emissions of greenhouse gases. These will depend on a variety of assumptions regarding human behaviour and activities, including population, economic growth, energy use and the sources of energy generation. Figure 18 shows *scenarios* of future

[7] See footnote 8 for an explanation of 'likely' as used by the IPCC.

[8] Model simulations of climate into the future depend on assumptions regarding future anthropogenic emissions of greenhouse gases, which in turn depend on assumptions about many uncertain factors involving human behaviour. They are therefore generally called 'projections' rather than 'predictions' to emphasise that what is being done is to explore likely future climates which arise from a range of assumptions regarding human activities.

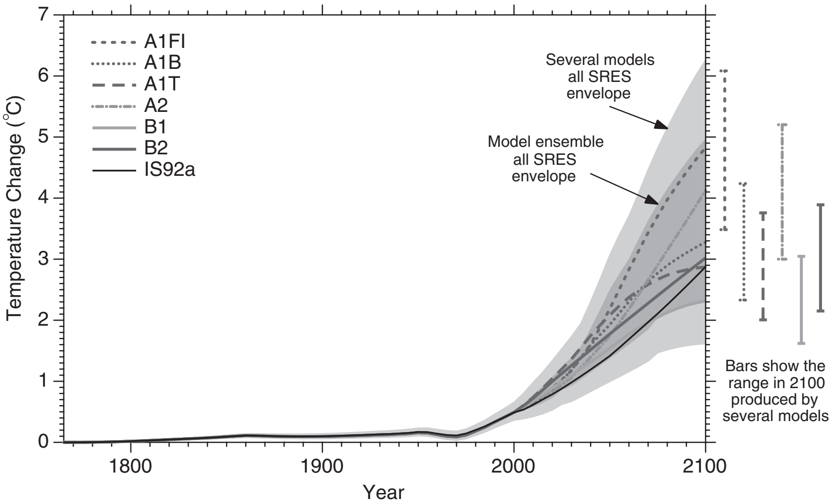

Figure 19. Change in global average temperature change since pre-industrial times to the end of the 21st century as simulated by seven climate models [70]. Historic anthropogenic global mean temperature change and future changes for the SRES and IS 92a scenarios calculated using a simple climate model tuned to seven AOGCMs (see section 6). The darker shading represents the envelope of the full set of 35 SRES scenarios using the average of the model results (mean climate sensitivity is 2.8˚C). The lighter shading is the envelope including all seven model projections (models climate sensitivity in the range 1.7–4.2˚C; the range of model results for each scenario is also shown by the bars on the rhs).

carbon dioxide emissions developed by the IPCC [67]; these are just examples of the many scenarios that have been developed.

The SRES scenarios are based on four different story lines [69]:

- A1 a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter and rapid introduction of new technologies, fossil fuel intensive (A1F1), emphasis on non-fossil-fuel sources (A1T) and balanced technologies (A1B);
- A2 a very heterogeneous world with continuously increasing population;
- B1 a convergent world with global population as A1 with rapid change to a service and information economy with emphasis on global solutions to economic, social and environmental sustainability;
- B2 a world with emphasis on local solutions to economic, social and environmental sustainability, increasing population at rate lower than A2.

7.2. Projections of global atmospheric temperature and precipitation

To develop projections of future climate, it is necessary first to turn the emission scenarios into greenhouse gas concentrations in the atmosphere (see section 4 and figure 18(*b*)) and then to radiative forcing (see section 5). Climate models incorporating the profiles of radiative forcing can then be run into the future so as to provide simulations of future climate. We have noted earlier that a measure for climate change that has been widely used is the change in global average temperature. Figure 19 shows projections of global atmospheric temperature rise from pre-industrial times to the end of the 21st century. It shows an increase of about 0.6˚C up to the year 2000 and an increase ranging from about 2˚C to about 6˚C by 2100, the wide

range resulting from the very large uncertainty regarding future emissions and also from the uncertainty that remains regarding the feedbacks associated with the climate response to the changing atmospheric composition (as described in section 6)[9].

Compared with the temperature changes normally experienced from day to day and throughout the year, changes of between 2˚C and 6˚C may not seem very large. But it is in fact a large amount when considering *globally averaged* temperature. Compare it with the 5˚C or 6˚C change in global average temperature that occurs between the middle of an ice age and the warm period in between ice ages (figure 8). The changes projected for the 21st century are from one-third to a whole ice age in terms of the degree of climate change!

The rate of change of global average temperature projected for the 21st century is in the range of 0.15–0.6˚C per decade—much larger than any rates of change the climate has experienced for at least the past ten thousand years as inferred from paleoclimate data. As we shall see when considering impacts (section 8), the ability of both humans and ecosystems to adapt to climate change depends critically on the rate of change.

In many modelling studies of climate change, doubled pre-industrial atmospheric CO_2 has often been introduced as a benchmark to assist in comparisons between different model projections and their possible impacts. Since other greenhouse gases are also increasing and contributing to the radiative forcing it is often helpful to convert other greenhouse gases to *equivalent* amounts of CO_2 that would give the same radiative forcing [71]. For instance, the increases to date in the greenhouse gases (including ozone) other than CO_2 produce about 50% of the radiative forcing due to the increase in CO_2 (see figure 13). This proportion will drop substantially during the next few decades as the growth in CO_2 becomes more dominant. For the set of IPCC scenarios, doubling of the equivalent CO_2 amount from pre-industrial times will occur between 2040 and 2070 depending on the scenario. Because of the slowing influence of the oceans, the full global average temperature increase of about 2.5˚C for doubled carbon dioxide will not be realized for 20 or 30 years after the doubling occurs.

So far, we have been presenting results solely for atmospheric surface temperature change. An even more important indicator of climate change is precipitation. With warming at the Earth's surface, increased evaporation from the oceans and from many land areas will lead, on average, to increased atmospheric water vapour content and therefore also, on average, to increased precipitation. The nature of the atmosphere's hydrological cycle dominated by the condensation of water vapour leads to an expectation that the atmosphere's average relative humidity should remain about the same irrespective of changes in the average surface temperature [72]. The atmosphere's water vapour content, therefore, should increase as its water holding capacity increases by about 6.5% per ˚C [10]. Model projections indicate increases in precipitation broadly related to surface temperature increases of about 3% per ˚C [73]—but also see section 7.5.

7.3. Regional patterns of climate change

So far we have been presenting climate change in terms of global averages. However, it is in the regional or local changes that the effects and impacts of global climate change will be felt. Because of the way the atmospheric circulation operates and the interactions that govern the behaviour of the whole climate system, climate change over the globe will not be at all uniform.

[9] Note that the uncertainty ranges in figure 17 do not include those that arise from lack of knowledge concerning climate feedbacks on the carbon cycle (see section 4.1).

[10] Related through the Clausius Clapeyron equation $e^{-1}\,\mathrm{d}e/\mathrm{d}T = L/RT^2$ where e is the saturation vapour pressure at temperature T, L the latent heat of evaporation and R the gas constant.

For instance, because of the smaller thermal capacity of the land surface, land areas typically experience 40% greater warming than ocean areas. Larger warming is also experienced at high northern latitudes in winter associated with reduced sea ice and snow cover.

Even larger variations in precipitation are projected. Although, on average, globally precipitation increases there are large regional variations and large areas where there are likely to be decreases in average precipitation and changes in its seasonal distribution. For instance, at high northern latitudes large increases are projected in winter and over south Asia in summer. Southern Europe, Central America, Southern Africa and Australia are likely to have drier summers.

Much natural climate variability occurs because of changes in, or oscillations between, persistent climatic patterns or regimes. Many such regimes originate because of strong connections between patterns of sea surface temperature and atmospheric circulation. The best known and most dominant pattern is the El Niño Southern Oscillation (ENSO). About every three to five years (often occurring around Christmas time—hence the name El Niño), movements in the Pacific ocean transport a large volume of warm water to a region of the south Pacific off the coast of Peru. Associated with this pattern, there occur droughts in Australia and many parts of Africa, floods in parts of the Americas and climate extremes elsewhere in the world. Further examples of climatic regimes are the Pacific, North Atlantic Anomaly (PNA), that tends to lead to very cold winters in the eastern United States and the North Atlantic Oscillation (NAO), which has a strong influence on the character of the winters in north-west Europe.

Important components of anthropogenic climate change can be expected to be in the form of changes in the intensity or frequency of established climate patterns illustrated by these regimes [74]. Although there is little consistency as yet between models regarding projections of many of these patterns, recent trends in the tropical Pacific for the surface temperature to become more El Niño-like are projected to continue by many models. There is also evidence that warming associated with increasing greenhouse gas concentrations will cause an intensification of the Asian summer monsoon and an increase of variability in its precipitation. The influence of increased greenhouse gases on major climate regimes, especially the El Niño, is an important and urgent area of research.

The large variations in regional forcing due to aerosols produce substantial regional variations in the climate response. Detailed regional information from the best climate models needs to be employed to assess the climate change under different assumptions about the increases in both greenhouse gases and aerosols.

7.4. Regional climate models

Most of the regional changes mentioned so far have been on the scale of continents; these can be studied with general circulation models of the kind described in section 6. For studies on smaller scales, however, such models possess severe limitations arising from the coarse size of their horizontal grid—typically 300 km. To overcome these limitations, regional climate models (RCMs) have been introduced with much higher resolution, typically about 50 km. They cover a limited region and are 'nested' in a global circulation model that defines the varying boundary conditions at the edges of an RCM. They have achieved considerable success in providing simulations of regional detail and extremes, especially for precipitation. However, it is important to realize that, because of the greater natural variability apparent in local climate compared with climate averaged over continental scales, climate change projections on local and regional scales are bound to be more uncertain than those on larger scales.

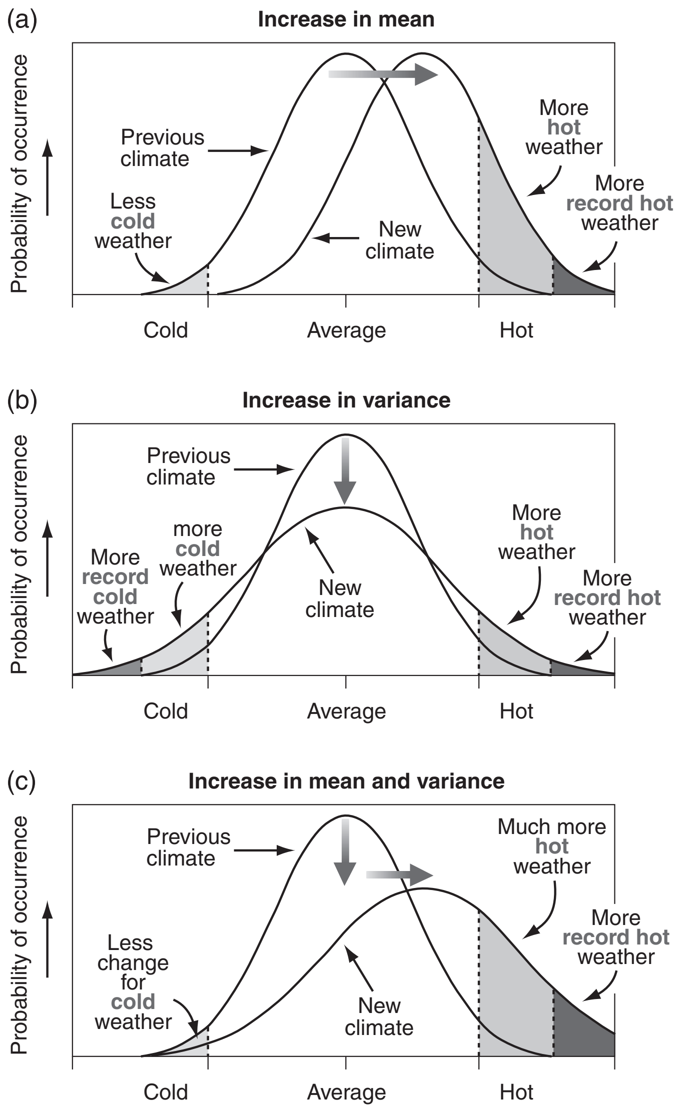

Figure 20. Schematic diagrams showing the effects on extreme temperatures when (*a*) the mean increases, leading to more record hot weather, (*b*) the variance increases and (*c*) when both the mean and the variance increase, leading to much more record hot weather [75].

7.5. Changes in climate extremes

Most of the presentation so far has concerned average climate. However, it is not the changes in average climate so much as the extremes of climate—droughts, floods, storms and extremes of temperature in very cold or very warm periods—that provide the largest impact on our lives.

The most obvious change to be expected in extremes is a large increase in the number and severity of extremely warm days (figure 20) coupled with a decrease in the number of extremely cold days. A number of model projections show a generally decreased daily variability of surface air temperature in winter and increased daily variability in summer in

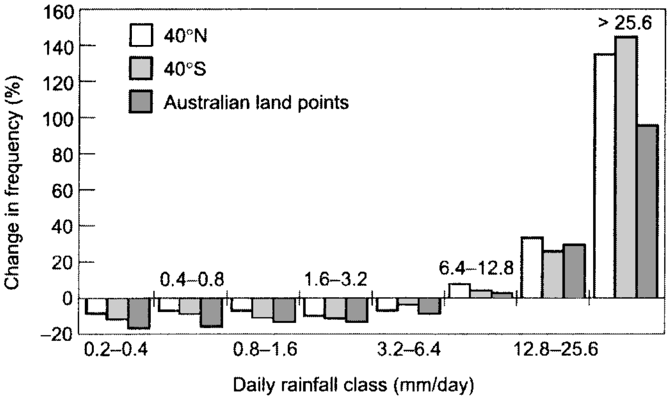

Figure 21. Changes in the frequency of occurrence of different daily rainfall amounts with doubled CO_2 as estimated by a CSIRO model in Australia [78].

Northern Hemisphere land areas, suggesting that the situation in figure 20(*c*) could apply in these areas (figure 26 shows an example).

However, the greatest impact is likely to occur with changes connected with precipitation events, especially precipitation intensity. Moderate rainfall soaks into the soil and benefits plants. However, the same rainfall falling with greater intensity in a shorter period can lead to floods, run off, less soil moisture and may also cause damage. In heavy rainfall events, the intensity is dependent on the total water vapour available from the volume of air drawn in by the storm's circulation [76]; this rises by about 6.5% per ˚C (section 7.2). Further, since many storms, especially in tropical areas, obtain most of their energy from the release of latent heat of condensation, larger increases in rainfall intensity could occur. Many model studies confirm these results (figure 21) that mean, with increasing temperature, a large rate of increase in the likelihood of floods. For instance, a recent modelling study (figure 22) has shown that, with doubled CO_2 concentration, the probability of extreme seasonal precipitation in winter is likely to increase over large areas of central and Northern Europe and to decrease over parts of the Mediterranean and north Africa. In parts of central Europe, increases are indicated in the return period of extreme rainfall events of about a factor of five (e.g. from 50 years to 10 years). Similar results have been obtained in a study of major river basins around the world [77].

Note also from figure 21 that the number of days with lighter rainfall events (less than 6 mm/day) is expected to decrease. This is because, with the more intense hydrological cycle, a greater proportion of the rainfall will fall in the more intense events and further, in regions of convection, the areas of downdraught become drier as the areas of updraught become more moist. In many areas with relatively low rainfall, therefore, the rainfall will tend to become less. Further, in such areas it is likely that the number of rainy days will be substantially fewer with more chance of prolonged periods of no rainfall at all; in other words, much more likelihood of drought. Further, the higher temperatures will lead to increased evaporation reducing the amount of moisture available at the surface—thus adding to the drought conditions. The proportional increase in the likelihood of drought is much greater than the proportional decrease in average rainfall. The impact of this is considered in more detail in section 8.

What about other climate extremes, intense storms or storm surges, for instance? Regarding tropical cyclones (hurricanes and typhoons), the energy for their development and maintenance largely comes from the latent heat of water that condenses in the clouds within the storms. Model projections and theoretical studies suggest that, if carbon dioxide concentration is doubled, the peak wind intensities will tend to increase by 5% or 10% and the mean and

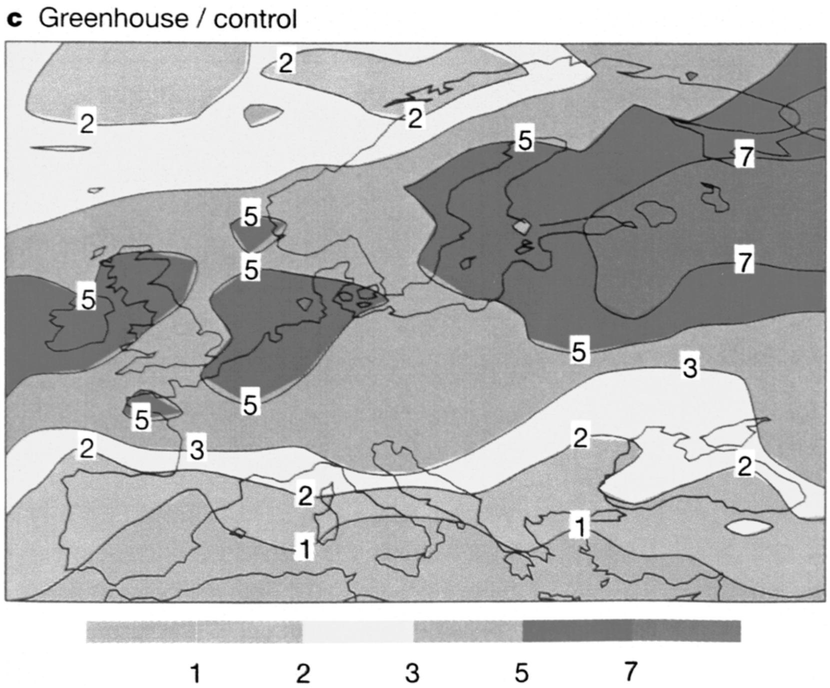

Figure 22. The changing probability of extreme season precipitation in Europe in winter as estimated from an ensemble of 19 runs with a climate model starting from slightly different initial conditions. The figure shows the ratio of probabilities of extreme precipitation events in the years 61–80 of 80 year runs that assumed an increase of CO_2 concentration of 1% per year (hence doubling in about 70 years) compared with control runs with no change in CO_2 [79].

peak precipitation intensities by 20% to 30%. However, although models can take all the relevant factors into account, because of the relatively large size of their grid, they are unable to simulate reliably all the detail of relatively small disturbances like tropical cyclones. There is no consistent evidence from model projections of changes in the frequency of tropical cyclones or their areas of formation.

Regarding storms at mid-latitudes, the various factors that control their incidence are complex. Two factors tend to an increased intensity of storms. The first, as with tropical storms, is that higher temperatures, especially of the ocean surface, tend to lead to more energy being available. The second factor is that the larger temperature contrast between land and sea, especially in the Northern Hemisphere, tends to generate steeper temperature gradients, which in turn generate stronger flow and greater likelihood of instability. The mid- to north-Atlantic region is one area where such increased storminess might be expected; a number of model projections under doubled carbon dioxide concentration show increase in the average intensity of depressions although not in their number [80]. However, there is little agreement in the underlying mechanisms leading to this result [81].

Many research centres are pursuing detailed studies of the influence of increased greenhouse gases on extreme events and climate variability; quantitative projections are urgently required. For some other extremes such as very small-scale phenomena (e.g. tornadoes, thunderstorms, hail and lightning) that cannot be simulated by global models there is currently insufficient information to assess recent trends, and understanding is inadequate to make firm projections.

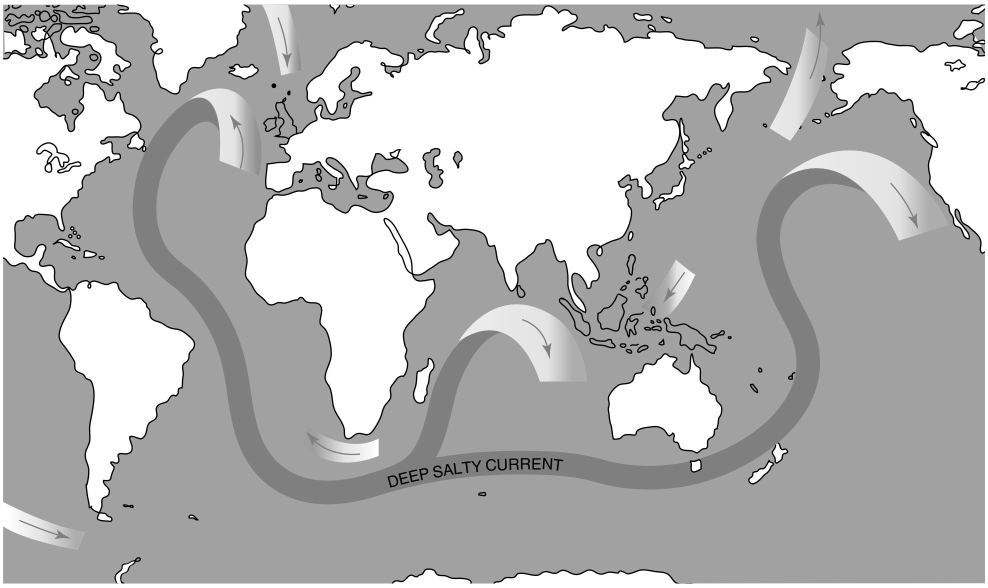

Figure 23. Illustrating deep water formation and the thermohaline circulation [84].

7.6. Longer-term climate change

From the beginning of the industrial revolution until 2000 the burning of fossil fuels released approximately 600 Gt of carbon in the form of CO_2 into the atmosphere. Under the SRES A1B scenario (figure 18) a further 1500 Gt will be released by the year 2100. The reserves of fossil fuels in total are sufficient to enable their rate of use to continue to grow well beyond the year 2100. If that were to happen the global average temperature would continue to rise and could, in the 22nd century, reach very high levels, perhaps up to 10˚C higher than today. The associated changes in climate would be correspondingly large and could well be irreversible [82].

Much of what has been presented so far has been concerned with the direct effects of increased temperature and precipitation. There are additional substantial non-linear effects that could result in large and irreversible changes. Three of these will be mentioned.

The first is that of positive feedbacks on the carbon cycle due to climate change, mentioned in section 4 (figure 12) and as an uncertainty in the caption to figure 18(*a*). Taking this effect into account would add about a further 1˚C to the projected increase in global average temperature in 2100 at the top end of the range shown in figure 19.

The second concerns possible changes in the ocean's thermohaline circulation (THC). This is a current that circulates in the deep ocean (figure 23) driven to a large degree by the descent of water in the Greenland sea and Labrador sea areas of the north Atlantic ocean. Water that has originated in the tropics and moved north in the Atlantic, undergoing a lot of evaporation, is both salty and cold—hence it is unusually dense and readily sinks. With global warming, there is additional fresh water input at high latitudes because of increased precipitation and ice melt. As a result, the THC will weaken and less heat will flow northward from tropical regions to the north Atlantic. All coupled ocean–atmosphere GCMs show this occurring, although in varying degrees, resulting in less warming in the region of the north Atlantic (including north-west Europe)—although none show actual cooling occurring in this region during the 21st century. There is also evidence that large changes in the THC have occurred in the past [83]. In the longer term, some models show the THC actually cutting off

completely after two or three centuries of increasing greenhouse gases. Intense research is being pursued—both observations and modelling—to elucidate further likely changes in the thermohaline circulation and their possible impact.

The third non-linear effect that concerns the major ice sheets in Greenland and Antarctica will be addressed when sea-level rise is considered in the next section.

8. The impacts of climate change

8.1. The complexity of impact assessment

We have seen that climate change is complex and variable both in space and time. The likely impacts on human communities and ecosystems will also be complex. There is also much variability in important factors relevant to climate change such as *sensitivity* (i.e. the degree to which a system is affected either adversely or beneficially), *adaptive capacity* (i.e. the ability of a system to adjust) and *vulnerability* (i.e. the degree to which a system is susceptible to or unable to cope with adverse effects). Different ecosystems, for instance, will respond very differently to changes in temperature, precipitation or other climate variables. For humans, it is the least developed countries that in general are most vulnerable; they are likely to experience more of the damaging climate extremes and also have less capacity to adapt.

A few impacts of climate change will be positive so far as humans and ecosystem productivity are concerned. For instance, in parts of Siberia or Northern Canada increased temperature will tend to lengthen the growing season with the possibility of growing a greater variety of crops. In some areas, increased carbon dioxide will aid the growth of some types of plants leading to increased crop yields (see section 8.4). However, because over centuries human communities have adapted their lives and activities to the present climate, most changes in climate will tend to produce adverse impacts. If changes occur rapidly, urgent and possibly costly adaptation to a new climate will be required by the affected community. An alternative might be for that community to migrate to a region where less adaptation would be needed—a solution that has become increasingly difficult or, in some cases, impossible in the modern crowded world. Further, adverse impacts are likely to lead to insecurity and conflicts particularly due to increased competition for scarce resources.

Assessment of the impacts of global warming is also made more complex because global warming is not the only human-induced environmental problem. Loss of soil and its impoverishment (through poor agricultural practice), over-extraction of groundwater and damage due to acid rain are examples of environmental degradations on local or regional scales that are having a substantial impact now [85]. They will tend to exacerbate the negative impacts arising from global warming.

The assessment of climate change impacts, adaptations and vulnerabilities draws on a wide range of physical, biological and social science disciplines and consequently employs a large variety of methods and tools. It is, therefore, necessary to integrate information and knowledge from these diverse disciplines. Such a process is often known as *Integrated Assessment.*

The following paragraphs will look briefly at various impacts in turn.

8.2. Sea-level rise

The largest contribution to sea-level rise in the 21st century is expected to be from the thermal expansion of ocean water as it warms. Calculation of the precise amount of expansion is complex because it depends critically on the water temperature and also because of the long time taken (decades to centuries) for warming at the surface to penetrate to lower ocean levels.

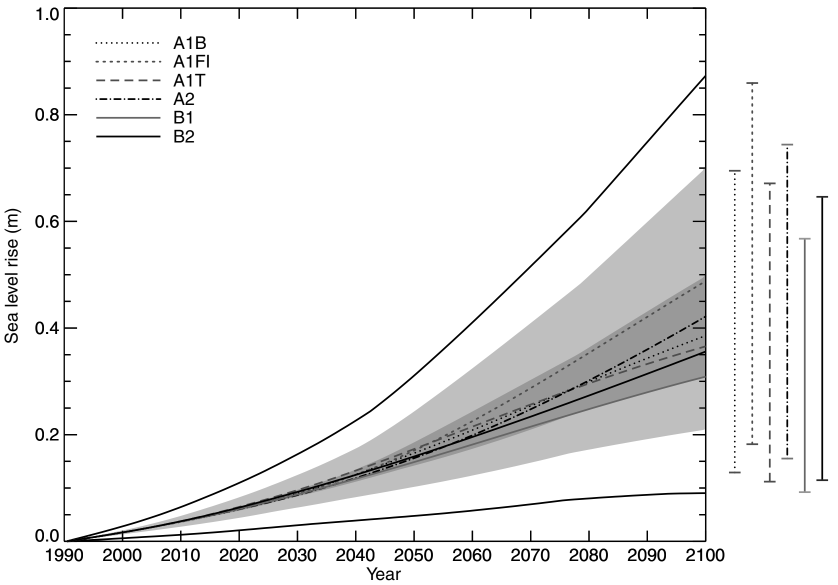

Figure 24. Global average sea-level rise 1990–2100 for the SRES scenarios [87]. Each of the lines identified in the key is the average of the AOGCMs for one of the six illustrative SRES scenarios. The region in dark shading shows the range of the average of AOGCMs for all 35 SRES scenarios. The region in light shading shows the range of all AOGCMs for all 35 scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainties in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet (see text). The bars at the right show the range in 2100 of all AOGCMs for the six illustrative scenarios.

Therefore, to calculate the sea-level rise due to thermal expansion—its global average and its regional variations—it is necessary to employ the results of an ocean climate model, of the kind described in section 6.

The other main contribution is expected to come from melting of glaciers. Substantial glacier retreat has occurred in recent decades adding an estimated 2–4 cm to the sea-level rise of between 10 and 20 cm in the 20th century [86]. If all glaciers outside Antarctica and Greenland were to melt, the rise in sea level would be about 50 cm (between 40 and 60 cm). The net contributions at the present time from the ice caps of Greenland and Antarctica are believed to be small (but see below).

The average sea-level rise during the 21st century for each of the SRES emission scenarios has been calculated by adding up the various contributions (figure 24). The large uncertainties in the estimates arise mainly from uncertainties in emissions scenarios, model uncertainty (cf figure 19) and glacier melt. The total range of uncertainty by 2100 is from about 10 to 90 cm.

The projections in figure 24 apply to the next 100 years. During that period, because of the slow mixing that occurs only a small part of the oceans will have warmed significantly. Sea-level rise resulting from global warming will, therefore, lag behind temperature change at the surface. During the following centuries, as the rest of the oceans gradually warm, sea level will continue to rise at about the same rate, even if the average temperature at the surface were to be stabilized.

What about the major ice sheets; will their contribution continue to be small in the future? For both ice-sheets there are two competing effects. In a warmer world, there is more water

vapour in the atmosphere that leads to more snowfall. But there is also more ablation (erosion by melting) of the ice around the boundaries of the ice-sheets and calving of icebergs during summer months. For Antarctica, the present estimates are that accumulation is greater than ablation, leading to a small net growth. However, it is possible that larger changes in the ice sheets may begin to occur. The Greenland ice sheet is probably the more vulnerable; its complete melting will cause a sea-level rise of about 7 m. Model studies of the ice sheet show that, with a rise in summer temperature in the region of Greenland of more than 3˚C—likely to be realized within a few decades—ablation will significantly overtake accumulation and melt down of the ice cap will begin. Such melt down is likely to be irreversible. If the temperature continued to rise to say 8˚C or more, much of the melt down would occur during the next 1000 years [88]. Turning to the Antarctic ice-sheet, the part that is of most concern is in the west of Antarctica (around 90˚ W longitude); its disintegration would result in about 6 m of sea-level rise. Because a large portion of it is grounded well below sea level it has been suggested that rapid ice discharge could occur if the surrounding ice shelves are weakened. In the absence of such rapid change, about which studies at present are inconclusive [89], the contribution of the West Antarctic Ice Sheet to sea-level rise over the next millennium will be less than 3 m [11].

A rise in average sea level of 10 cm by 2030 and about half a metre by the end of the 21st century (typical values from figure 24) may not seem a great deal. Many people live sufficiently above the level of high water not to be directly affected. However, half of humanity inhabits the coastal zones around the world. Within these, the lowest lying are some of the most fertile and densely populated. To people living in these areas, even a fraction of a metre increase in sea level can add enormously to their problems [90][12]. Some of the areas that are especially vulnerable are first, large river delta areas, for instance Bangladesh, second, areas very close to sea level where sea defences are already in place, for instance the Netherlands and third, small low-lying islands in the Pacific and other oceans. Here, we just consider the example of Bangladesh.

Bangladesh is a densely populated country of about 120 million people located in the complex delta region of the Ganges, Brahmaputra and Meghna Rivers [91]. About 10% of the country's habitable land (with about 6 million population) would be lost with half a metre of sea-level rise and about 20% (with about 15 million population) would be lost with a 1 m rise [92] (figure 25). Estimates of the sea-level rise are of about 1 m by 2050 (compounded by 70 cm due to subsidence because of land movements and removal of groundwater and 30 cm from the effects of global warming) and nearly 2 m by 2100 (1.2 m due to subsidence and 70 cm from global warming) [93]—although there is a large uncertainty in these estimates. Further exacerbation of the impact will arise through the combination of sea-level rise with likely increases in the intensity of storm surges in that region. Further, increased salt water intrusion into ground water will occur in many low lying regions. Similar situations to that in Bangladesh exist in other parts of south-east Asia [94], the Nile delta region of Egypt [95] and delta regions in other parts of Africa and the Americas.

It is not only in places where there is dense population that there will be adverse effects. The world's wetlands and mangrove swamps currently occupy an area of about a million square kilometres (the figure is not known very precisely), equal approximately to twice the area of France. They contain much biodiversity and their biological productivity equals or exceeds that of any other natural or agricultural system. Over two-thirds of the fish caught for human consumption, as well as many birds and animals, depend on coastal marshes and swamps for

[11] Professor Chris Rapley, of the British Antarctic Survey has recently reported observations of acceleration in the movement of the outlet glaciers from the West Antarctic Ice Sheet, that could lead to surging as shelves break away.
[12] The regional chapters also contain information about impacts of sea-level rise.

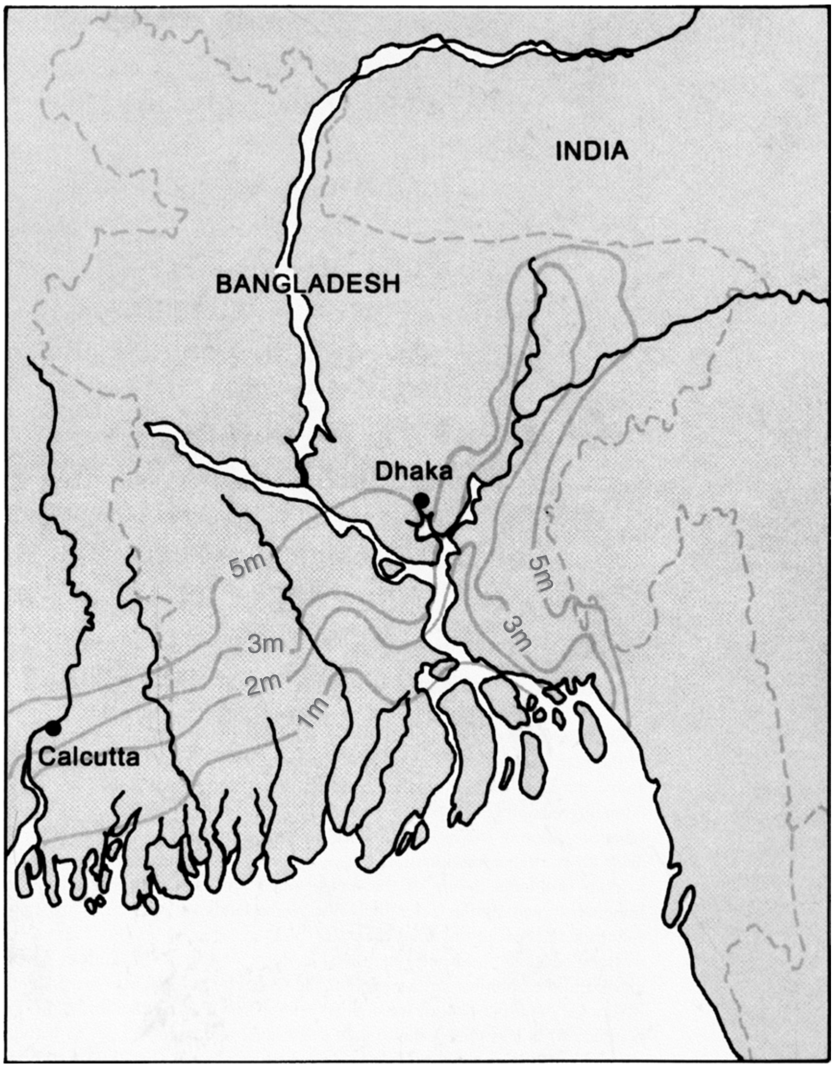

Figure 25. Land affected in Bangladesh by various amounts of sea-level rise [96].

part of their life cycles, so they are vital to the total world ecology. These areas could not adjust to the rapid rate of sea-level rise that is likely and in many cases would be unable to extend inland. Net loss of wetland area will therefore occur [97].

8.3. Fresh water resources

The global water cycle is a fundamental component of the climate system. Water is cycled between the oceans, the atmosphere and the land surface. Water is also an essential resource for humans and for ecosytems. During the last 50 years water use has grown over threefold [98]; it now amounts to about 10% of the estimated global total of river and groundwater flow from land to sea. Increasingly, water is used for irrigation. In India about 75% of available water is so used. Water from major rivers is often shared between nations; its growing scarcity is a potential

source of conflict. In many areas, groundwater extraction greatly exceeds its replenishment—a situation that cannot continue indefinitely.

With global warming, there will be substantial changes in water availability, quality and flow. On average, some areas will become wetter and others drier. Substantial changes in variations of flow during the year will also occur as glaciers and snow cover diminishes leading to less spring melt. Much of these changes will exacerbate the current vulnerability regarding water availability and use. Especially vulnerable will be continental areas where decreased summer rainfall and increased temperature result in a substantial loss in soil moisture and increased likelihood of drought.

Even greater impact is likely to occur because of increased frequency and intensity of extremes, especially floods and droughts (see section 7.5). Such disasters are the most damaging disasters the world experiences; on average they cause more deaths, misery and economic loss (see section 8.8) than other disasters. They are especially damaging to developing countries where, in general, they are more likely to occur and where there is inadequate infrastructure to cope with them. Impacts of climate change on fresh water resources are likely to be exacerbated by other pressures, e.g. population growth, land-use change, pollution and economic growth.

Some of the adverse impact on water supplies can be reduced by taking appropriate alleviating action, by introducing more careful and integrated water management [99] and by introducing more effective disaster preparedness in the most vulnerable areas.

8.4. Agriculture and food supply

Climate change would affect agriculture and food supply through its impact on crops, soils, insects, weeds, diseases and livestock. Three factors are particularly important; changes in water availability (see section 8.3), changes in temperature and the effect of increased CO_2 on plant growth. Higher CO_2 concentrations stimulate photosynthesis, enabling some plants (e.g. wheat, rice and soya bean) to fix carbon at a higher rate. This is why in glasshouses additional CO_2 may be introduced artificially to increase productivity. Under ideal conditions it can be a large effect (for doubled CO_2 up to an average of +30% [100]). However, under real conditions on the large scale, where water and nutrient availability are also important factors, increases tend to be substantially less than what is potentially possible [101]. For instance, for cereal crops in mid-latitudes, potential yields are projected to increase for small increases in temperature (2–3˚C) but decrease for larger temperature increases[13].

In a world influenced by global warming, crop patterns will change. But the changes will be complex; economic and other factors will take their place alongside climate change in the decision-making process. To estimate the effect of climate change on world food supply, elaborate modelling studies have been carried out [103]. These start with climate change scenarios for different locations and times that are inserted into crop models that then produce projected changes in crop yields. Included also are farm level adaptations (e.g. planting date shifts, more climatically adapted varieties, irrigation and fertilizer application). These yield changes are then employed as inputs to a world food trade model that includes assumptions about global parameters, such as population growth and economic factors. The outputs from the total process provide information projected up to the 2080s on food production, food prices and the number of people at risk of hunger.

The main results from this modelling work for the 21st century are that yields at mid- to high latitudes are expected to increase and at low latitudes (especially the arid and sub-humid tropics) to decrease—a pattern that becomes more pronounced as time progresses. Many

[13] Because of large uncertainties, the IPCC only ascribed it medium confidence (see footnote 18 for explanation).

parts of Africa are particularly likely to be seriously affected. For the world as a whole, with appropriate adaptation, the effect on total global food supply is not likely to be large. However, these studies are complex and at an early stage; they have not yet adequately taken into account the likely effects of climate extremes (especially the incidence of drought), of increasingly limited water availability or of other factors such as the integrity of the world's soils (currently being degraded at an alarming rate) [104] or feedbacks between land-use changes and the climate system (cf figure 13).

Perhaps the most serious issue exposed by the studies is that climate change is likely to affect countries very differently. Production in developed countries with relatively stable populations may increase, whereas that in many developing countries with growing populations is likely to decline. Disparity between developed and developing nations will tend to become much larger. Since agriculture is the main source of employment in many developing countries, there could be enhanced deprivation and large numbers of environmental refugees (see section 8.8).

In looking to future needs, two activities are particularly important. First, there is large need in developing countries for technical advances in agriculture (e.g. in crop breeding and management) requiring investment and widespread local training. These could immediately assist in the improvement of productivity in marginal environments. Second, improvements need to be made in the availability and management of water for irrigation, especially in arid or semi-arid areas of the world.

8.5. Ecosystems

About 10% of the world's land area is under cultivation. The rest is to a greater or lesser extent unmanaged by humans. Of this about 30% is natural forest. Within this area climate is the dominant factor determining the distribution of biomes. Large changes in this distribution have occurred during the relatively slow climate changes in the past. It is the very rapid rate of change of climate that will cause excessive stress on many systems. How much it matters depends on the species and the degree of climate change (e.g. temperature increase or water availability). Two particularly vulnerable types of species are trees and coral. The viability of some large areas of tropical forests under climate change is of especial concern. Many corals are already suffering from bleaching caused by increased ocean temperatures. Further, as large quantities of extra carbon dioxide are dissolved in the oceans, their acidity increases posing a serious threat to living systems in the oceans especially to corals[14].

A further concern about natural ecosystems relates to the species diversity and the unprecedented loss of species and hence of biodiversity due to the impact of climate change—especially when that impact is added to other stresses on ecological systems due to human activities (e.g. land conversion or degradation, deforestation and pollution) [105].

8.6. Human health

Human health will be affected by many of the impacts described in previous paragraphs such as deteriorating water availability, food shortages and more intense and more frequent floods and droughts. Increased spread of insect-borne diseases, such as malaria, is also likely in a warmer world. The main direct effect of climate change on humans themselves will be that of heat stress in the extreme high temperatures that will become more frequent and more widespread especially in urban populations. Studies using data from large cities where heat

[14] Information presented by the Plymouth Marine Laboratory to the Climate Change conference held in Exeter UK in February 2005.

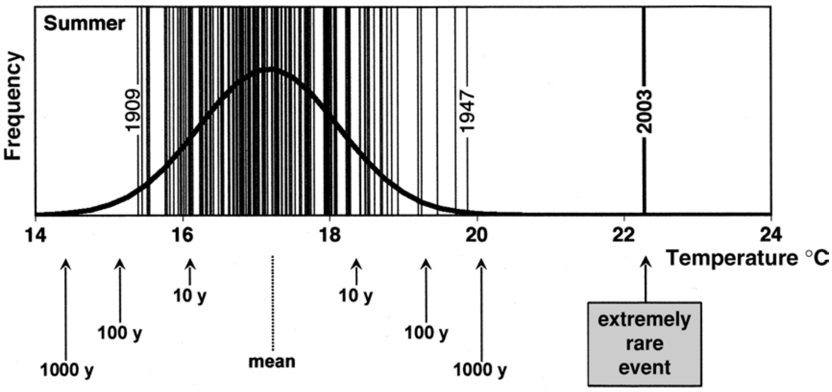

Figure 26. Distribution of average summer temperatures (June, July, August) in Switzerland from 1864 to 2003 showing a fitted Gaussian probability distribution—standard deviation 0.94˚C . The 2003 value is 5.4 standard deviations from the mean showing it to be an extremely rare event. Also shown are return periods calculated from conventional statistics assuming no warming trend.

waves commonly occur show death rates that can be doubled or tripled during days of unusually high temperatures [106]. On the positive side, mortality due to periods of severe cold in winter will be reduced.

An example of record extreme high temperatures is the heat wave in Europe during June, July and August, 2003. At many locations temperatures rose above 40˚C. In France, Italy, the Netherlands, Portugal and Spain over 20 000 additional deaths were attributed to the unrelenting heat. Figure 26 illustrates the extreme rarity of this event. Studies show that it is very likely that a large part of its cause is due to the increase in greenhouse gases, that by 2050 such a summer would be likely to be the norm and by 2100 would likely be a cool summer [107].

8.7. Adaptation and mitigation

An integrated view of anthropogenic climate change is presented in figure 27. It shows two kinds of action that can be taken—*adaptation* to reduce the impacts of climate change as it occurs and *mitigation* to reduce emissions of greenhouse gases that in turn will reduce the amount of climate change. Some of the impacts of anthropogenic climate change are already becoming apparent and a degree of adaptation is already a necessity. Many adaptation options have already been identified [109] that can reduce the adverse impacts of climate change and can also produce ancillary benefits, but they cannot prevent all damages. Of particular importance is the requirement for adaptation to extreme events and disasters such as floods, droughts and severe storms [110]. Vulnerability to such events can be substantially reduced by more adequate preparation[15]. Options for mitigation are listed in section 11.

Associated with both the science and the impacts of climate change are considerable uncertainties—many of these have been mentioned in the preceding sections. Politicians and others making decisions are, therefore, faced with the need to weigh all aspects of uncertainty against the desirability and the cost of the various actions that can be taken in response to the threat of climate change.

[15] As an example of progress with respect to disaster preparedness, the International Red Cross has recently formed a Climate Change Unit based in the Netherlands.

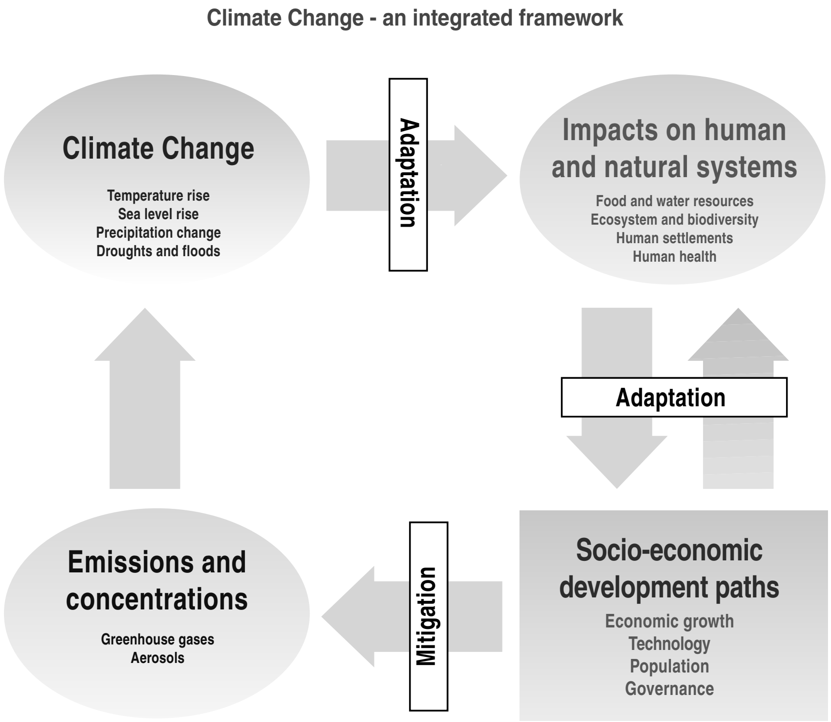

Figure 27. Climate change—an integrating framework [111]. A complete cycle of cause and effect is shown beginning with economic activity (lower right-hand corner) that results in emissions of greenhouse gases (of which CO_2 is the most important) and aerosols. These emissions lead to changes in atmospheric composition and hence to changes in climate that impact both humans and natural ecosystems and affect human livelihood, health and development. An anticlockwise arrow represents other effects of development on human communities and natural systems, for instance changes in land use that lead to deforestation and loss of biodiversity.

8.8. Costing the impacts

Probably the largest impact of climate change will be that of the increased number and intensity of extreme events. We noted in section 3 the recent increase in extreme events and the interest of insurance companies who have tracked increasing damage from them in recent decades (figure 7). Not that insured losses are a good guide to total loss. For instance, the insured losses for Hurricane Mitch that hit Central America in 1998 were small. However, 9000 people died and the losses in Honduras and Nicaragua, respectively, amounted to about 70% and 45% of their annual gross national product (GNP) [112]. China is a country particularly prone to natural disasters; from 1989 to 1996 they resulted in an average annual loss equivalent to nearly 4% of GDP [113].

A number of economic studies have attempted to estimate the average annual cost in monetary terms of the impacts that would arise under the climate change due to a doubling of pre-industrial atmospheric CO_2 concentration that will likely occur later in the 21st century [114]. If some allowance is added for the impact of extreme events, the estimates are typically around 1% or 2% of GDP for developed countries and around 5 per cent or more for developing countries—in general substantially greater than the cost of taking action to slow the onset of global warming or reduce its overall magnitude (see section 10). But it is

important to realize that these attempts at monetary costing can only represent a part of the overall impact story. Many of them have not allowed for the substantial costs of adaptation. Further, any assessment of impacts has to take into account the cost in human terms and the large social and political disruption some of the impacts will bring. In particular, it is estimated that there could be up to 3 million new environmental refugees each year or over 150 million by the middle of the 21st century [115].

9. International policy and action

As observational and modelling tools for studying the climate advanced during the 1970s and 1980s, the attention of scientists became increasingly directed towards the effects on the climate of human activities. A scientific conference in 1985 organized by the Scientific Committee on Problems of the Environment (SCOPE) a committee of the International Council of Scientific Unions led to an important publication [116] that described the adverse effects that could result from continued and increased anthropogenic emissions of CO_2. That in turn led to increasing awareness amongst politicians of the scale of the potential problem. Two important international bodies were created, one in 1988 concerned with science (the IPCC) and one in 1992 with policy (the Framework Convention on Climate Change (FCCC)). These will be introduced briefly in turn.

9.1. The Intergovernmental Panel on Climate Change (IPCC)

The IPCC was formed jointly by two United Nations bodies, the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) with a remit to prepare thorough assessments of climate change, its causes and effects. The Panel established three working groups, one to deal with the science of climate change, one with impacts and a third with policy responses. The IPCC has produced three main comprehensive reports [117], in 1990, 1995 and 2001 together with a number of special reports covering particular issues. This review has already referred widely to these reports.

Three important factors have contributed to the authority and success of the IPCC's reports [118]. The first is the emphasis on delineating between what is known with reasonable certainty and what is uncertain—differentiating so far as possible between degrees of uncertainty[16]. The second is the involvement in the writing and reviewing of the reports of as many as possible of the world's climate scientists, especially those leading the field. For the third assessment report in 2001, those taking part had grown to 123 lead authors and 516 contributing authors, together with 21 review editors and 420 expert reviewers involved in the review process. The thorough debate by scientists during the assessment process ensures that the scientific community is well informed on a broad front. No previous scientific assessments on this or any other subject have involved so many scientists so widely distributed both as regards their countries and their scientific disciplines.

A third factor arises because the IPCC is an intergovernmental body and governments are involved in its work. Each report includes a Summary for Policymakers (SPM), the wording of which is approved in detail at a plenary meeting of the Working Group, the object being to reach agreement on the science and on the best way of presenting it to policymakers with accuracy and clarity. It is the presentation that is particularly the responsibility of the government representatives. At the plenary meeting in Shanghai where the 2001 Working Group I SPM was unanimously agreed, 99 government representatives were present, along

[16] Refer to footnote 8 for explanation of IPCC's quantification of uncertainty.

with 45 representatives from the scientific community. Having been part of the process, governments as well as scientists feel ownership of the Reports—an important factor when it comes to policy negotiations.

9.2. The Framework Convention on Climate Change (FCCC)

The FCCC, signed by over 160 countries at the United Nations Conference on Environment and Development held in Rio de Janeiro in June 1992, came into force in 1994. It has set the agenda for action to slow and stabilize climate change. The FCCC recognizes the reality of global warming together with the uncertainties associated with predictions of climate change and states that mitigating action needs to be taken despite the uncertainties. It also points out that developed countries should take the lead in this action.

The long-term objective of the Convention, expressed in Article 2, is

> *to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

In setting this objective, the Convention has recognized that it is only by stabilizing the concentration of greenhouse gases (especially CO_2) that rapid climate change can be halted.

Up to the end of 2004, 10 sessions of the Conference of the Parties to the Climate Convention have taken place. Those since November 1997 have largely been concerned with the Kyoto Protocol, the first formal binding legislation promulgated under the Convention that commits industrialized countries (known as Annex I countries) to specific reductions in emissions (typically by between 5% and 8%) of a basket of greenhouse gases[17] from their level in 1990 to their average from 2008–2012, called the first commitment period. The Protocol also requires that a second commitment period be defined for which negotiations must start no later than 2005. With the ratification of the Protocol by Russia, the Protocol came into force on 16 February 2005—although without ratification by the USA and Australia.

The Kyoto Protocol includes three special mechanisms to assist in emissions reductions by industrialized countries, namely *Joint Implementation (JI)* that encourages projects that reduce emissions or increase removals by sinks in the territories of other industrialized countries; *the Clean Development Mechanism (CDM)* that encourages projects that reduce emissions in developing countries (certified emission reductions generated by JI and CDM can be used by industrialized countries to help meet their emission targets); and *Emissions Trading* that allows the purchase of 'assigned amount units' of emissions from other industrialized countries that find it easier, relatively speaking, to meet their emissions targets. The overall cost of mitigating climate change is reduced as countries utilize lower cost opportunities to curb emissions or increase removals, irrespective of where those opportunities exist. These mechanisms include the use of sinks of CO_2 (e.g. through aforestation) although capping arrangements limit their use as offset to emissions elsewhere [119].

The Kyoto Protocol is an important start to the mitigation of climate change through reductions in greenhouse gas emissions. With its complexity and its diversity of mechanisms

[17] The basket of greenhouse gases covered by the Kyoto Protocol contains CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and SF_6. The effectiveness of each gas is calculated from its global warming potential (GWP) relative to CO_2—see section 5.

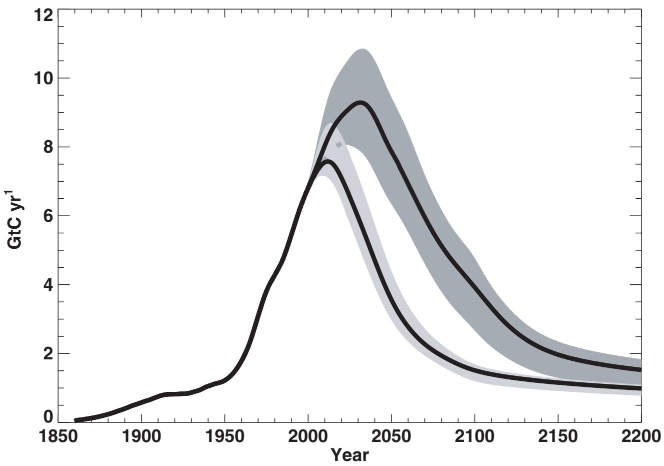

Figure 28. Profiles of the emissions of carbon dioxide from fossil fuel burning in gigatonnes of carbon per year that would lead to stabilization of carbon dioxide in the atmosphere at levels of 450 ppm (lower curve) and 550 ppm (upper curve) estimated from the UK Hadley Centre carbon cycle model with the effects of climate–carbon-cycle feedbacks included. Up to the year 2000 the actual emissions are shown. The shadings show an estimate of the uncertainties in the calculations. Emissions from land-use change have been assumed as in the SRES B1 scenario [67].

for implementation it also represents a considerable achievement in international negotiation and agreement. The much more substantial longer-term reductions that will be necessary for the decades that follow the first commitment period are considered in the next section.

10. The stabilization of climate

Climate can only be stabilized if the concentrations of greenhouse gases are also stabilized as required by the FCCC.

10.1. Stabilization of CO_2 concentration

Carbon dioxide emissions are growing substantially year by year (figure 18). Because of the long life time of CO_2 in the atmosphere, even if the level of emissions were stabilized, its concentration would continue to grow. For stabilization of its concentration, emissions must fall well below today's levels and eventually be no greater than the level of persistent natural sinks (see section 4.1)—probably no more than 0.1 Gt per year [120]. In figure 28, profiles of emissions from fossil fuel burning are shown that will lead to stabilization of CO_2 at levels of 450 ppm and 550 ppm (approximately double its pre-industrial value). The profiles shown include an estimate of climate–carbon-cycle feedback [121] as described in section 4.1 (figure 12). Many different profiles that are consistent with stabilization could have been chosen. The ones shown begin by following the current rate of increase; they then provide a smooth transition to a time of stabilization that is approximately 2100 for 450 ppm and 2150 for 550 ppm. To a first approximation, the stabilized concentration level depends more on the accumulated amount of carbon emitted up to the time of stabilization than on the exact concentration path followed en route to stabilization. Alternative pathways that assume higher emissions in earlier years would require steeper reductions in later years. If the atmospheric concentration of CO_2 is to remain below about 500 ppm, the future global annual

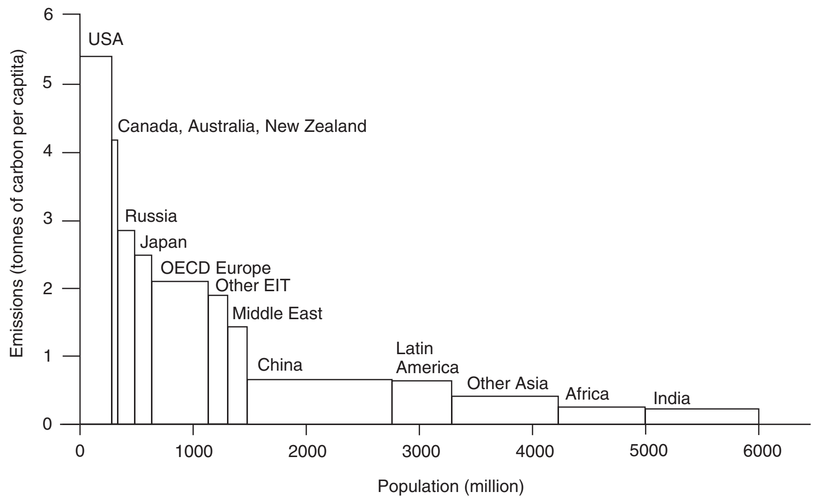

Figure 29. Carbon dioxide emissions in 2000 from different countries or groups of countries expressed per capita plotted against their population [123].

emissions averaged over the 21st century should not exceed the 1990 level of global annual emissions.

It is instructive also to look at annual emissions of CO_2 expressed per capita. Averaged over the world in 2000 they were just over 1 tonne (as carbon) per capita but they varied very much from country to country (figure 29). For developed countries and transitional economy countries in 2000 they averaged 2.8 tonnes (ranging downwards from about 5.5 tonnes for the USA) while for developing countries they averaged about 0.5 tonnes. Looking ahead to the years 2050 and 2100, even if the world population rises to only about 7 billion (as with SRES scenarios A1 and B1) under the profiles of carbon dioxide emissions leading to stabilization at concentrations of 450 and 550 ppm the per capita annual emissions averaged over the world would be about 0.6 tonnes and 1.1 tonnes, respectively, for 2050 and 0.3 tonnes and 0.7 tonnes, respectively, for 2100[18]—much less than the current value of about 1 tonne.

10.2. Stabilization of other greenhouse gases

Other than CO_2, methane is the main greenhouse gas of importance. Actions have already been taken to reduce some of the methane emission sources, e.g. leaks from oil and gas wells and landfill sites. The rate of methane increase has recently slowed significantly although all the reasons for this are not well understood. There is more uncertainty about nitrous oxide as its sources and sinks are not well known. However, it is only a relatively small contributor to the forcing—to date equivalent to about 10 ppm of carbon dioxide. However, even under the assumption of no future increases, the contributions to date of greenhouse gases other than CO_2 are equivalent to a CO_2 increase of around 70 ppm[19]. Under this assumption, a stabilization of CO_2 at 450 ppm, for instance, leads to an equivalent CO_2 level of about 520 ppm.

[18] The per capita figures in this paragraph include emissions from both fossil fuel burning and land-use change.
[19] The figure of 70 ppm applies when the CO_2 level is 450 ppm. Because the addition is non linear, the effect of additional gases expressed in terms of equivalent CO_2 depends on the CO_2 level to which the addition is made, e.g. at 370 ppm the addition is about 60 ppm and at 550 ppm it is about 90 ppm.

10.3. Realization of the convention objective

First, what about the choice of stabilization level for CO_2? It will be clear, for instance from figure 28, that stabilization below about 400 ppm would require an almost immediate drastic reduction in emissions breaching the criterion 'that economic development can proceed in a sustainable manner'. Taking into account the guidance provided by the Convention and the range and severity of likely impacts described in section 8 [124], it is becoming increasingly recognized that the aim should be for levels below 550 ppm carbon dioxide equivalent (i.e. below about 480 ppm for CO_2 itself if allowance is made for other greenhouse gases—see section 10.2). To mention, for example, two statements regarding this choice coming from very different bodies. First, the European Union has proposed setting a limit for the rise in global average temperature of 2˚C [20]. Since the best estimate of global average temperature rise for doubled pre-industrial CO_2 (560 ppm) is 2.5˚C, a rise of 2˚C would occur with a carbon dioxide concentration of about 430 ppm allowing for the effect of other gases at their 1990 levels. The second statement comes from Lord John Browne, the Group Chief Executive of British Petroleum, one of the largest of the world's oil companies. He recognizes the danger of global warming and the challenge it presents and has stated that, for CO_2, 'stabilization in the range 500–550 ppm is possible, and with care could be achieved without disrupting economic growth'[21].

Having considered the stabilization level, how can the nations of the world work together to realize it in practice? Within the FCCC, four principles are contained that should be at the basis of negotiations concerned with future emissions reductions to mitigate climate change. They are the Principle of Sustainable Development (as in the FCCC Objective), the Precautionary Principle, the Polluter-Pays Principle and the Principle of Equity. This latter includes *intergenerational* equity, or weighing the needs of the present generation against those of future generations, and *international* equity, or weighing the balance of need between developed nations and the developing world. Striking this latter balance is particularly difficult because of the great disparity in current carbon dioxide emissions between the world's richest nations and the poorest nations (figure 29), the continuing demand for fossil fuel use in the developed world and the understandable desire of the poorer nations to escape from poverty through development and industrialization.

An example of how the approach to stabilization for CO_2 might be achieved is illustrated in figure 30. It is based on a proposal called 'Contraction and Convergence' that originates with the Global Commons Institute (GCI) [125], a non-governmental organization based in the UK. The envelope of carbon dioxide emissions is one that leads to stabilization at 450 ppm (without climate feedbacks included), although the rest of the proposal does not depend on that actual choice of level. Note that, under this envelope, global fossil-fuel emissions rise by about 15% to about 2025; they then fall to less than half the current level by 2100. The figure illustrates the division of emissions between major countries or groups of countries as it has been up to the present. Then, the simplest possible solution is taken to the sharing of emissions between countries by proposing that, from some suitable date (in the figure, 2030 is chosen), emissions be allocated on the basis of equal shares per capita. From now until 2030 the division is allowed to converge from the present situation to that of equal per capita shares—hence the 'contraction and convergence'. The further proposal is that arrangements to trade the CO_2 allocations be made.

[20] European Commission Communication on a Community Strategy on Climate Change; Council of Ministers Conclusion, 25–26 June 1996

[21] From speech to the Institutional Inverstors Group, London, 26th November 2003.

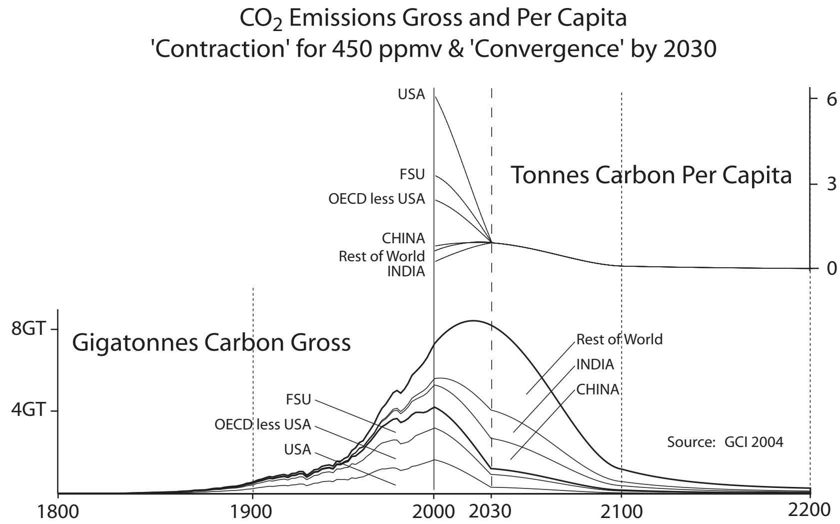

Figure 30. Illustrating the 'Contraction and Convergence' proposal of the Global Commons Institute for achieving stabilization of CO_2 concentration. The envelope of CO_2 emissions illustrated is one that leads to stabilization at 450 ppm (but the effect of climate–carbon cycle feedbacks is not included). For major countries or groups of countries, up to the year 2000, historic emissions are shown. After 2030 allocations of emissions are made on the basis of equal shares per capita on the basis of population projections for that date. From now until 2030, smooth 'convergence' from the present situation to that of equal shares is assumed to occur. In the upper part of the diagram, the per capita contributions that apply to different countries or groups of countries are shown; FSU = Former Soviet Union; OECD = Organisation for Economic Cooperation and Development.

The 'Contraction and Convergence' proposal addresses all of the four principles mentioned above. In particular, through its equal per capita sharing arrangements it deals with the question of international equity, and the proposed trading arrangements ensure that the greatest 'polluters' pay. Its simple logic makes it a strong candidate for a long-term solution. What has yet to be worked out is how the 'convergence' can be implemented—although that is a problem contained within any proposal for a solution.

11. The mitigation of climate change [126]

The mitigation of climate change requires large reductions in anthropogenic emissions of greenhouse gases, especially CO_2. The last section addressed the reductions necessary for CO_2 to be stabilized. The UK Royal Commission on Environmental Pollution (RCEP) has recommended that the UK should aim to reduce by 60% by 2050 to allow some room for increase by developing nations [127]—a target that has been accepted by the UK government. To achieve such reductions very large changes are required in the way energy is used and generated. In particular,

- Much energy is currently wasted or used inefficiently. Many studies have shown that in most developed countries improvements in energy efficiency of 30% or more can be achieved at little or no net cost or often with significant overall saving. Buildings and transport are two sectors, each contributing around one third of total CO_2 emissions, where opportunities for significant savings exist. But industry and individuals will

generally require not just encouragement, but modest incentives if the savings are to be realized.

- Much of the necessary technology is available for renewable energy sources, which can go a long way towards replacing energy from fossil fuels, to be developed and implemented—for instance from 'modern' biomass (energy crops or waste), solar energy (photovoltaic and thermal), wind (on- and off-shore) and tidal energy (barrages, 'lagoons' or tidal streams). For this to happen on the required scale, economic frameworks with adequate incentives are urgently required. Policy options available include the removal of subsidies, carbon or energy taxes (which recognize the environmental cost associated with the use of fossil fuels) and tradeable permits coupled with capping of emissions.
- Methods for the capture and sequestration of CO_2 underground should be rapidly developed enabling some continuing use of fossil fuels. Further, nuclear energy, which is already responsible for generating 16% of the world's electricity, can continue to provide non-fossil-fuel energy in the short and medium term [128]. The problem of dangerous proliferation of nuclear material probably prevents it being a significant contributor in the long term. It is possible that, in the longer term, nuclear fusion could become a useful, cheap and safe energy source [129].
- Carbon from the atmosphere can also be sequestered in forests. Schemes for reducing deforestation (with its associated CO_2 emissions) and encouraging the planting of trees will also bring substantial ancillary benefits.
- Arrangements are needed to ensure that technology is available for all countries (including developing countries through technology transfer) to develop their energy plans with high efficiency and to deploy renewable energy sources as widely as possible.
- With world investment in the energy industry running at over one million million US dollars per year, there is a great responsibility on both governments and industry to ensure that energy investments (including an adequate level of research and development) take long-term environmental requirements fully into account.

What about the cost of mitigation? Economic studies show that, if changes are planned and phased with care, the cost will not be large. For instance a study commissioned by the UK Cabinet Policy Innovation Unit (PIU) estimated that to reduce emissions by 60% by 2050 would cost less than six months' reduction in economic growth in 50 years [130]. Other economic studies have come up with similar estimates [131].

12. The future challenge

Science and technology have a large part to play as the world community meets the challenge posed by anthropogenic climate change. All the natural sciences are involved in research to reduce the uncertainties regarding the details, extent and timing of climate change. To reduce scientific uncertainty in projections of climate change for the 21st century, it is particularly required to achieve improved knowledge and understanding of cloud-radiation feedback and climate–carbon-cycle feedbacks, more quantitative information about climate extremes, and better performance from both global and regional climate models.

Technology, both academic and industrial, has large contributions to make to solutions to the problems of adaptation and mitigation. Social and economic sciences need to explore imaginative ways of harnessing the energies and potential of financial and political institutions. Especially important are the following emphases [132]. First, global warming is a global problem and *global solutions* are required. Second, an *integrative, holistic approach* is needed that seeks to integrate perspectives from both the natural and the social sciences. Third, the aim

must be *to find solutions not just characterize problems.* Applied research seeking solutions is just as challenging and worthy as so-called fundamental research identifying and describing the problems. Fourth, since action by everybody is required, *everybody needs to be made aware and adequately informed.*

These actions require clear policies, commitment and resolve on the part of governments, industries and individual consumers. *Urgent* action is required for three reasons. The first is *scientific*. Because the oceans take time to warm, there is a lag in the response of climate to the increase of greenhouse gases (section 3.1). A commitment to substantial climate change already exists, much of which will not be realized for several decades. The second reason is *economic*. Energy infrastructure, for instance, in power stations, lasts typically for 30 to 50 years. It is much more cost effective to begin now to phase in the required infrastructure changes rather than having to make them much more rapidly later. The third reason is *political*. Countries like China and India are industrializing very rapidly. They need to do so in ways that are much more efficient and with much smaller greenhouse gas emissions than has been done in the developed world. The Climate Convention requires that developed countries lead by example. As the World Energy Council point out 'the real challenge is to communicate the reality that the switch to alternative forms of supply will take many decades, and thus the realization of the need, and commencement of the appropriate action, must be *now*' (their italics) [133].

Acknowledgments

I am grateful to many colleagues associated with the IPCC and the Hadley Centre who have assisted with the preparation and review of this report, and in particular to Chris Folland, Geoff Jenkins, Tim Palmer, David Griggs, Jonathan Gregory, Peter Cox, Chris Jones, Simon Brown, Peter Stott, Richard Betts, Jason Lowe, Debbie Hemming, Cath Senior, Mat Collins, Gareth Jones and Linda Livinston, also to Matt Lloyd and Carol Miller of CUP who assisted with the figures.

References

[1] IPCC 2001 *Third Assessment Report* published in 4 vols: *Climate Change 2001, The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press)
IPCC 2001 *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed J J McCarthy *et al* (Cambridge: Cambridge University Press)
IPCC 2001 *Climate Change 2001: Mitigation* ed B Metz *et al* (Cambridge: Cambridge University Press)
IPCC 2001 *Climate Change 2001: Synthesis Report* R T Watson and core writing team (ed) 2001 (Cambridge: Cambridge University Press)
Also available on IPCC web site, www.ipcc.ch. Two previous comprehensive reports also published by CUP in 1990 and 1995—see footnote 18.

[2] Houghton J 2004 *Global Warming: The Complete Briefing* 3rd edn (Cambridge: Cambridge University Press) p 349

[3] More details of the history can be found in Mudge F B 1997 The development of greenhouse theory of global climate change from Victorian times *Weather* **52** 13–16

[4] From Kiehl J T and Trenberth K E 1997 *Bull. Am. Met. Soc.* **78** 197–208

[5] Spectrum taken with the infrared interferometer spectrometer flown on the satellite Nimbus 4 in 1971 and described by Hanel R A *et al* 1971 *Appl. Opt.* **10** 1376–82

[6] More detailed information about the enhanced greenhouse effect in Houghton J T 2002 *The Physics of Atmospheres* 3rd edn (Cambridge: Cambridge University Press) chapter 14

[7] For information about how the records have been put together and how the quality of the data has been investigated see Folland C K *et al* IPCC 2001 *Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press) chapter 2—also summarized in Houghton J 2004 *Global Warming: The Complete Briefing* 3rd edn (Cambridge: Cambridge University Press)

[8] Based on Folland C K *et al* 2001 Global temperature change and its uncertainties since 1861 *Geophys. Res. Lett.* **106** 2621–4

Jones P D and Moberg A 2003 Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001 *J. Clim.* **16** 206–23 (figure prepared by Folland C K)

[9] From Mann M E and Jones P D 2003 Global surface temperature over the past two millennia *Geophys. Res. Lett.* **30** 1820, doi: 10.1029/2003GL017814, (C) American Geophysical Union

[10] Since 1979, remote sensing measurements from satellite mounted instruments have been made of the global temperature structure of the lower troposphere. Over much of this period, trends in global averaged tropospheric temperature (approximately 3 km altitude) from satellite data have been reported as much smaller than those in surface temperature data—a fact that has been used to call into question the integrity of surface data trends. This provides no reason, however, to challenge the surface data as the two records are not measuring the same quantity and there are a number of possible reasons for differences between them, e.g. the influence on the lower troposphere record of cooling at higher levels due to the enhanced greenhouse effect. See Fu Q and Johanson C M 2004 *J. Clim.* **17** 4636–40. Further, more recent calibration of the satellite data has brought the trends from the satellite data set much more in line with surface temperature trends. See Grody N C *et al* 2004 *J. Geophys. Res.* **109** D24104, doi:10.1029/2004JD005079

[11] Cubasch U *et al* 2001 Projections of future climate change *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) figure 9.1, chapter 9

[12] Levitus S *et al* 2005 Warming of the world's ocean *Geophys. Res. Lett.* **32** 1955–98 L02604, doi:10.1029/2004GL021592,2005

[13] Figure 8.1 from Vellinga P *et al* 2001 Insurance and other financial services *Climate Change 2001, Impacts Adaptation and Vulnerability* ed J J McCarthy *et al* (Cambridge: Cambridge University Press) chapter 8

[14] Further details in Jones P D and Mann M E 2004 Climate over past millennia *Rev. Geophys.* **42** RG2002

von Storch H *et al* 2004 Reconstructing past climate from noisy data *Science* **306** 679–82

Osborn T J and Briffa K R 2004 *Science* **306** 621–2

Moberg A *et al* 2005 Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data *Nature* **433** 613–17

[15] Moberg A *et al* 2005 *loc cit*

[16] Adapted from Raynaud D *et al* 1993 The ice core record of greenhouse gases *Science* **259** 926–34

[17] Folland C K *et al* 2001 *IPCC 2001 Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press) chapter 2, figure 2.22

EPICA Community Members 2005 Eight glacial cycles from an Antarctic ice core *Nature* **429** 623–8

[18] Adapted from Broecker W S and Denton G H 1990 What drives glacial cycles? *Sci. Am.* **262** 43–50

[19] See also Kump L R 2002 Reducing uncertainty about CO_2 as a climate driver *Nature* **419** 188–90

[20] Berger A and Loutre M F 2002 *Science* **297** 1287–8

[21] For a summary of how the radiative effect of water vapour contribute to climate see Maurellis A and Tennyson J 2003 *Phys. World* **16** 29–33

[22] Figure 1.1 from Bolin B *et al* 2000 Global perspective *Land Use, Land-Use Change and Forestry* ed R T Watson *et al*, *A Special Report of the IPCC* (Cambridge: Cambridge University Press) chapter 1, p 30

[23] From IPCC 2001 *Climate Change 2001*, *The Scientific Basis* (Cambridge: Cambridge University Press) 2001 Technical Summary, figure 10

[24] The entries in the first four rows are from table 3.3 in Prentice C *et al* 2001 The carbon cycle and atmospheric carbon dioxide IPCC 2001, chapter 3 *Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press) (note that the ranges quoted represent 67% certainty). The entries in the 'partitioning of land–atmosphere flux' are from House J I *et al* 2003 Reconciling apparent inconsistencies in estimates of terrestrial CO_2 sources and sinks *Tellus* B **55** 345–63

See also table 1.2 in Watson R T *et al* (ed) 2000 *Land Use, Land-Use Change and Forestry, an IPCC Special Report* (Cambridge: Cambridge University Press)

[25] For more detail see House J I 2003 *loc cit*

[26] see Jones C D and Cox P M 2001 *Atmos. Sci. Lett.* doi.1006/asle.2001.0041; the respiration rate varies approximately with a factor $2^{(T-10)/10}$

[27] Knorr W *et al* 2005 Long-term sensitivity of soil carbon turnover to warming *Nature* **433** 298–301 suggest that this feedback could be larger than currently predicted by global models

[28] Cox P M *et al* 2004 Amazon die-back under climate-carbon cycle projections for the 21st century *Theor. Appl. Climatol.* **78** 137–56

[29] From the UK Hadley Centre, see Cox P M *et al* 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model *Nature* **408** 184–7

[30] The ratio of the enhanced greenhouse effect of a molecule of methane compared to a molecule of carbon dioxide is known as its global warming potential (GWP); a definition of GWP is given in section 5. The figure of about 8 given here for the GWP of methane is for a time horizon of 100 years—see Lelieveld J and Crutzen P J 1992 *Nature* **355** 339–41

see also Prather M *et al Climate Change 2001: The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) chapter 4

Ramaswamy V *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) chapter 6.

[31] Gedney N *et al* 2004 Climate feedback from wetland methane emissions *Geophys. Res. Lett.* **31** 20503, doi:10.1029/2004GL020919, suggest that positive climate feedback of methane emissions due to increased temperature of wetlands, could lead to significant increase in atmospheric methane concentration by 2100

[32] Taking into account the loss processes due to reaction with OH in the troposphere, chemical reactions in and soil loss lead to a lifetime of about 10 years. However the effective lifetime of methane against a perturbation in concentration in the atmosphere (the number quoted here) is complex because it depends on the methane concentration. This is because the concentration of the radical OH (interaction with which is the main cause of methane destruction), because of chemical feedbacks, is itself dependent on the methane concentration (more details in Prather M *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) chapter 4

[33] For more detail, see Scientific Assessment of Ozone Depletion: 1998 Global Ozone Research and Monitoring *Project – Report* No 44, World Meteorological Organisation, Geneva, Switzerland, p 732

[34] Prather M *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton (Cambridge: Cambridge University Press) chapter 4

[35] More detail on this and the radiative effects of minor gases and particles can be found in Ramaswamy V *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton (Cambridge: Cambridge University Press) chapter 6

[36] Penner J E *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) chapter 5

Also Kaufman Y J *et al* 2002 A satellite view of aerosols in the climate system *Nature* **419** 215–23

[37] Sato M *et al* 2003 Global Atmospheric black carbon inferred from AERONET *Proc. Natl Acad Sci. USA* **100** 6319–24

[38] Hansen J and L Nazarenko 2003 Soot climate forcing via snow and ice albedos *Proc. Natl Acad. Sci. USA* **101** 423–8

[39] Studies of other stars are providing further information, see Nesme-Ribes E *et al* 1996 *Sci. Am.* 31–6

[40] See detailed discussion of possible solar forcing in section 11 of chapter 6 of Ramaswamy V *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton (Cambridge: Cambridge University Press)

[41] From Ramaswamy V *et al* 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton (Cambridge: Cambridge University Press) chapter 6, figure 6.6

[42] For more detail on components of radiative forcing and their spatial variations see Hansen J *et al* 2002 Climate forcings in GISS simulations *J. Geophys. Res.* **107** 4347, doi:10.1029/2001JD001143

[43] For more complete information of the effects of aviation see Penner J E *et al* (ed) 1999 Aviation and the global atmosphere *IPCC Special Report* (Cambridge: Cambridge University Press)

[44] For a comprehensive review see Trenberth K E and Stepaniak D P 2004 The flow of energy through the Earth's climate system *Q. J. R. Met. Soc.* **130** 2677–701

[45] Richardson L F 1965 *Weather Prediction by Numerical Processes* (Cambridge: Cambridge University Press) 1922 reprinted (New York: Dover)

[46] For more detail see for instance Houghton J T 1992 *The Physics of Atmospheres* 3rd edn (Cambridge: Cambridge University Press) 2002 and Trenberth K E (ed) 1992 *Climate System Modelling* (Cambridge: Cambridge University Press) chapters 11 & 14

[47] Associated with water vapour feedback is also *lapse rate feedback* which occurs because associated with changes of temperature and water vapour content in the troposphere are changes in the average lapse rate (the rate of fall of temperature with height). Such changes lead to this further feedback which is generally much smaller in magnitude than water vapour feedback but of the opposite sign, i.e. negative instead of positive. Frequently, when overall values for water vapour feedback are quoted the lapse rate feedback has been included. For more detail see Houghton J T 2002 *The Physics of Atmospheres* 3rd edn (Cambridge: Cambridge University Press)

[48] The magnitude and even the sign of the water vapour feedback has been questioned e.g. see Lindzen R S 1990 *Bull. Am. Met. Soc.* **71** 288–99. It clearly varies a great deal in space in time. For a thorough discussion

of this see Stocker T F *et al* 2001 Physical climate processes and feedbacks *Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press) chapter 7, section 7.2.1.1

[49] For a comprehensive account of ocean processes see Seidler G *et al* (ed) 2001 *Ocean Circulation and Climate (International Geophysics Series)* vol 77 (New York: Academic)

[50] Trenberth K E and Caron J M 2001 Estimates of meridional atmosphere and ocean heat transports *J. Clim.* **14** 3433–43

[51] see McAvaney B J *et al* 2001 Model validation *Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press) chapter 8

[52] Hansen J *et al* 1992 Potential climate impact of Mt Pinatubo eruption *Geophys. Res. Lett.* **19** 215–18
Also quoted in Houghton J T *et al* (ed) 1996 *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press) Technical summary

[53] Graf H-E *et al* 1993 Pinatubo eruption winter climate effects: model versus observations *Clim. Dynam.* **9** 61–73

[54] Palmer T N 2000 Predicting uncertainty in forecasts of weather and climate *Rep. Prog. Phys.* **63** 71–116

[55] Lorenz E 1963 *J. Atm. Sci.* **20** 130–41

[56] Houghton J T 1991 The predictability of weather and climate *Phil. Trans. R. Soc. Lond.* A **337** 521–72

[57] Mitchell J F B 2004 Can we believe predictions of climate change? *Q. J. R. Met. Soc.* **130** 2341–60

[58] Murphy J M *et al* 2004 Quantifying uncertainties in climate change using a large ensemble of global climate model predictions *Nature* **430** 768–72

[59] Stainforth D A *et al* 2005 Uncertainty in predictions of the climate response to rising levels of greenhouse gases *Nature* **433** 403–6

[60] Fjortoft R 1953 *Tellus* **1** 33–52
Also see Houghton J T 2002 *The Physics of Atmospheres* 3rd edn (Cambridge: Cambridge University Press) pp 138–42

[61] More detail in Palmer T N 2000 Predicting uncertainty in forecasts of weather and climate *Rep. Prog. Phys.* **63** 71–116

[62] Houghton J T *et al* (ed) 2001 Policymakers' summary *Climate Change 2001: The Scientific Basis* (Cambridge: Cambridge University Press), Simulations from model at Hadley Centre, UK

[63] Stott P A 2003 Attribution of regional-scale temperature changes to anthropogenic and natural causes *Geophys. Res. Lett.* **14** 1728, doi: 10.1029/2003GL017324

[64] Allen M R *et al* 2000 Quantifying the uncertainty in forecasts of anthropogenic climate change *Nature* **407** 617–20

[65] Gregory J M *et al* 2004 Simulated and observed decadal variability in ocean heat content *Geophys. Res. Lett.* **31** L15312, doi:10.1029/2004GL020258

[66] Houghton J T *et al* (ed) 2001 Summary for policymakers *Climate Change2001: The Scientific Basis* (Cambridge: Cambridge University Press)

[67] Nakicenovic N *et al* 2000 *IPCC Special Report on Scenarios* (Cambridge: Cambridge University Press)

[68] Leggett J *et al* 1992 Emission scenarios for the IPCC: an update *Climate Change 1992: The Supplementary Report to the IPCC Assessments* (Cambridge: Cambridge University Press) pp 69–95

[69] For more detailed summary of Story Lines see Watson R T and core writing team (ed) 2001 *Climate Change 2001: Synthesis Report* (Cambridge: Cambridge University Press) pp 10–11

[70] Cubasch U *et al* 2001 Projections of future climate change *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) chapter 9, figure 9.13 and 9.14

[71] The assumption that greenhouse gases may be treated as equivalent to each other is a good one for many purposes. However, because of the differences in their radiative properties, accurate modelling of their effect should treat them separately. More details of this problem are given in Gates W L *et al* 1992 Climate modelling, climate prediction and model validation *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment* ed J T Houghton *et al* (Cambridge: Cambridge University Press) pp 171–5

[72] Allen M R and Ingram W J 2002 *Nature* **419** 224–32

[73] See Allen M R and Ingram W J 2002 *Nature* **419** 224–32 who explain that the increase of precipitation is controlled by the availability of energy as well as of water vapour

[74] For more on this see Palmer T N 1993 *Weather* **48** 314–25
Palmer T N 1999 *J. Clim.* **12** 575–91

[75] From Climate Change 2001: The Scientific Basis *(IPCC) 2001 Report* (Cambridge: Cambridge University Press) figure 2.32

[76] Trenberth K E *et al* 2003 The changing character of precipitation *Bull. Am. Met. Soc.* **84** 1205–17
Allen M R and Ingram W J 2002 *Nature* **419** 224–32

[77] Milly P C D *et al* 2002 Increasing risk of great floods in a changing climate *Nature* **415** 514–17

[78] From Pittock A B *et al* 1991 quoted in *Climate Change 1992: The Supplementary Report to the IPCC Assessment* ed J T Houghton *et al* 1992 (Cambridge: Cambridge University Press) p 120

[79] From Palmer T N and Raisanen J 2002 *Nature* **415** 512–14 The extreme precipitation events at the base of the study are those with winter precipitation greater than the mean plus two standard deviations that have probability in the control runs of 2.5% or a return period of about 40 years

[80] Hall N M J *et al* 1994 Storm tracks in a high-resolution GCM with doubled carbon dioxide *Q. J. R. Met. Soc.* **120** 1209–30

Carnell R E and Senior C A 1998 Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols *Clim. Dyn.* **14** 369–83

Knippertz P *et al* 2000 Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment *Clim. Res.* **15** 109–22

[81] Cubasch U *et al* 2001 Projections of future climate change *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) chapter 9

[82] For a brief review of the long term challenge of climate change see Hasselmann K *et al* 2003 *Science* **302** 1923–5

[83] Rahmstorf S 2002 Ocean circulation and climate during the past 120,000 years *Nature* **419** 207–14

[84] After Broecker W S and Denton G H 1990 What drives glacial cycles? *Sci. Am.* **262** 43–50

[85] See for instance *Global Environmental Outlook 3* (*UNEP Report*) Earthscan 2002

Also Goudie A 2000 *The Human Impact on the Natural Environment* 5th edn (Cambridge, MA: MIT Press)

[86] For further details see Church J A *et al* 2001 Changes in sea level *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) chapter 11

[87] Figure 11.12 from Church J A *et al* 2001 Changes in sea level *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) chapter 11

[88] Gregory J M *et al* 2004 *Nature* **428** 616

Toniazzo T 2004 *J. Clim.* **17** 21–33

[89] See Church J A *et al* 2001 Changes in sea level in *Climate Change 2001: The Scientific Basis, IPCC 2001 Report* (Cambridge: Cambridge University Press) chapter 11

[90] For detailed information about impacts of sea level rise see *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed J J McCarthy *et al* (Cambridge: Cambridge University Press) chapter 6 (especially R F McLean *et al* Coastal zones & marine systems)

[91] For a comprehensive account of the impact of climate change on Bangladesh see Warrick R A and Ahmad Q K (ed) 1996 *The Implications of Climate and Sea Level Change for Bangladesh* (Dordrecht: Kluwer)

[92] Nicholls R J and Mimura N 1998 Regional issues raised by sea level rise and their policy implications *Clim. Res.* **11** 5–18

[93] Broadus J M 1993 Possible impacts of, and adjustments to, sea-level rise: the cases of Bangladesh and Egypt *Climate and Sea-Level Change: Observations, Projections and Implications* ed R A Warrick *et al* 1993 (Cambridge: Cambridge University Press) pp 263–75. Note that, because of variations in the ocean structure, sea-level rise in Bangladesh would be somewhat above average.

[94] From report entitled *Climate Change due to the Greenhouse Effect and its Implications for China* published in 1992 by the Worldwide Fund for *Nature*, Gland, Switzerland

[95] Broadus J M 1993 Possible impacts of, and adjustments to, sea-level rise: the cases of Bangladesh and Egypt *Climate and Sea-level Change: Observations, Projections and Implications* ed R A Warrick *et al* (Cambridge: Cambridge University Press) pp 263–75

[96] From Broadus J M 1993 Possible impacts of, and adjustments to, sea-level rise: the cases of Bangladesh and Egypt *Climate and Sealevel Change: Observations, Projections and Implications* ed R A Warrick (Cambridge: Cambridge University Press) pp 263–75—adapted from Milliman J D *et al* 1989 Environmental and economic implications of rising sea-level and subsiding deltas: the Nile and Bangladesh examples *Ambio* **18** 340–5

[97] McLean R F *et al* 2001 Coastal zones and marine ecosystems *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed J James McCarthy *et al* (Cambridge: Cambridge University Press) chapter 6

[98] Shilomanov I A and Rodda J C (ed) 2003 *World Water Resources at the Beginning of the* 21st *Century* (Cambridge: Cambridge University Press)

[99] See Arnell N *et al* 2001 Hydrology and water resources *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed J James McCarthy *et al* (Cambridge: Cambridge University Press) chapter 4

[100] Reilly J *et al* 1996 Agriculture in a changing climate *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change* ed R T Watson *et al* (Cambridge: Cambridge University Press) chapter 13

[101] More detail on impact on ecosystems and biodiversity loss in Gitay H *et al* 2001 Ecosystems and their goods and services (section 5.3) *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed James J McCarthy *et al* (Cambridge: Cambridge University Press) chapter 5

[102] This statement is from the Policymakers' summary *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed James J McCarthy *et al* 2001 (Cambridge: Cambridge University Press)

[103] Parry M *et al* 1999 Climate change and world food security: a new assessment *Global Environ. Change* **9** S51–67

[104] *Global Environmental Outlook-3* UNEP and Earthscan 2002, pp 63–5

[105] More detail in Gitay H *et al* 2001 Ecosystems and their goods and services, chapter 5 (section 5.3) *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed James J McCarthy *et al* (Cambridge: Cambridge University Press)

[106] Kalkstein I S 1993 Direct impact in cities *Lancet* **342** 1397–9

[107] Stott P A *et al* 2004 Human contribution to the European Heatwave of 2003 *Nature* **432** 610–4

[108] Schar C *et al* 2004 The role of increasing temperature variability in European summer heatwaves *Nature* **427** 332–6

[109] Table 3.6 from *Climate Change 2001: Synthesis Report* ed Watson R T 2001 and core writing team *IPCC Report* (Cambridge: Cambridge University Press)

[110] see *Global Environmental Outlook 3—UNEP and Earthscan* 2002, pp 274–75

[111] Fig SPM-1 from the Summary for policymakers *Climate Change 2001, Synthesis Report* ed R T Watson *et al* 2001 (Cambridge: Cambridge University Press)

[112] Table 14.2 in Mata L J and Campos M 2001 Latin America *Climate Change 2001: Impacts, Adaptation and Vulnerability* ed J J McCarthy *et al* 2001 (Cambridge: Cambridge University Press)

[113] *Global Environmental Outlook 3 (UNEP Report)* 2002 London, Earthscan, p 272

[114] Pearce D W *et al* 1996 The social costs of climate change *Climate Change 1995: Economic and Social Dimensions of Climate Change* ed J Bruce *et al* (Cambridge: Cambridge University Press). Also see Houghton J 2004 *Global Warming: The Complete Briefing* 3rd edn (Cambridge: Cambridge University Press) chapter 7

[115] Myers N and Kent J 1995 Environmental exodus: an emergent crisis in the global arena *Climate Institute Report* Washington DC

[116] SCOPE 29 1986 *The Greenhouse Effect, Climate Change and Ecosystems* ed B Bolin *et al* (Chichester: Wiley)

[117] Houghton J T (ed) *et al* 1990 *Climate Change, The IPCC Scientific Assessment* (Cambridge: Cambridge University Press)

McG Tegart W J *et al* (ed) 1990 *Climate Change, The IPCC Impacts Assessment* (Canberra: Australian Government Publishing Service)

Houghton J T *et al* (ed) 1996 *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press)

Watson R T *et al* (ed) 1996 *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change* (Cambridge: Cambridge University Press)

Bruce J *et al* (ed) 1996 *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge: Cambridge University Press)

Houghton J T *et al* (ed) 2001 *Climate Change 2001, The Scientific Basis* (Cambridge: Cambridge University Press)

McCarthy J J *et al* (ed) 2001 *Climate Change 2001: Impacts, Adaptation and Vulnerability* (Cambridge: Cambridge University Press)

Metz B *et al* ed 2001 *Climate Change 2001: Mitigation* (Cambridge: Cambridge University Press) Also see IPCC web site www.ipcc.ch

[118] See Houghton J 2002 An overview of the IPCC and its process of science assessment *Global Environmental Change* ed R E Hester and R M Harrison (Issues in Environmetnal Science and Technology, No 17, Royal Society of Chemistry, UK, 2002)

See also news articles on the IPCC 2001 Shooting the messenger *Nature* **412** 103

Consensus science, consensus politics *Nature* **412** 112–14

[119] More details of the Kyoto Protocol and of the detailed arrangements for the inclusion of carbon sinks can be found in *Land Use, Land-Use Change and Forestry* ed Watson R T *et al* 2000 *A special Report of the IPCC* (Cambridge: Cambridge University Press) and on the FCCC web site <www.unfccc.int/resource/convkp.html>

[120] Prentice I C *et al* 2001 The carbon cycle and atmospheric carbon dioxide *Climate Change 2001, The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) chapter 3

[121] Cox P M *et al* 2000 Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model *Nature* **408** 184-7
C D Jones *et al* 2003 *Tellus* **55-B** 642–8
[122] Figure provided by Chris Jones of the Hadley Centre UK. These stabilization curves follow the CO_2 concentration curves and result in the temperature profiles shown in figure SPM 6 (*b*) and (*c*) from Summary for policymakers *IPCC 2001 Synthesis Report* (Cambridge: Cambridge University Press) 2001
[123] From Grubb M 2003 The economics of the Kyoto Protocol *World Economics* **4** 145
[124] Arnell N W *et al* 2002 The consequences of CO_2 stabilization for the impacts of climate change *Climatic Change* **53** 413–46
[125] Further details on the GCI Web-site, www.gci.org.uk
[126] Metz B *et al* (ed) 2001 *Climate Change 2001: Mitigation* (Cambridge: Cambridge University Press)
[127] RCEP 22nd *Report Energy—The Changing Climate* 2000, see www.rcep.org.uk
[128] Nuclear Energy: the future climate *Report* Royal Society and the Royal Academy of Engineering, p 76, 1999
[129] See McCraken G and Stott P 2004 *Fusion, the Energy of the Universe* (New York: Elsevier/Academic)
[130] www.cabinet-office.gov.uk/innovation/2002/energy/report/index.htm
[131] Watson R T and core writing team (ed) 2001 *Climate Change 2001: Synthesis Report* Summary for policymakers (Cambridge: Cambridge University Press)
[132] Clark W C 2003 *Sustainable Science: Challenges for the New Millennium*. An Address given at the opening of the Zuckerman Institute, University of East Anglia, Norwich, UK, 4 September 2003, http://sustainabilityscience.org/ists.docs/clark_zicer_opening030904.pdf
[133] Energy for tomorrow's world—the realities, the real options and the agenda for achievement *WEC Commission Report* World Energy Council, 1993, p 88