Chapter 2

CAUSES AND EFFECTS OF CLIMATE CHANGE

How, and why, has the Earth's atmosphere changed as a result of massive use of fossil fuels? If carbon dioxide emissions continue to increase, what effects will that have on temperatures, and on sea level? What are the likely consequences of such changes? What are the issues the world community now has to face?

2.1 There is now a broad scientific consensus that the climate is changing as a result of burning fossil fuels. The detailed evidence can be found in the report of the Second Assessment, carried out in 1995, by the body established by the United Nations for this purpose, the Intergovernmental Panel on Climate Change (IPCC),[1] and in popular accounts.[2] IPCC is at present carrying out a further review of the evidence in order to produce a Third Assessment, which will be published in 2001. We set out here the key points about the occurrence of climate change (2.2-2.18), its possible scale (2.19-2.26) and its likely effects (2.27-2.35), and outline a framework for considering the appropriate response (2.36-2.41).

The process of global warming

2.2 The Earth receives energy from the sun and loses heat to space. The *greenhouse effect,* shown in simplified form in figure 2-I, is a natural process that has been known for more than a century. It occurs because some of the gases present in the atmosphere are *greenhouse gases:* they allow most of the radiation from the sun through to warm the surface of the Earth, but (because it has a different wavelength) they absorb the heat given off from the Earth's surface. They then radiate part of that heat out to space and part back to Earth, thus further warming the surface of the Earth.

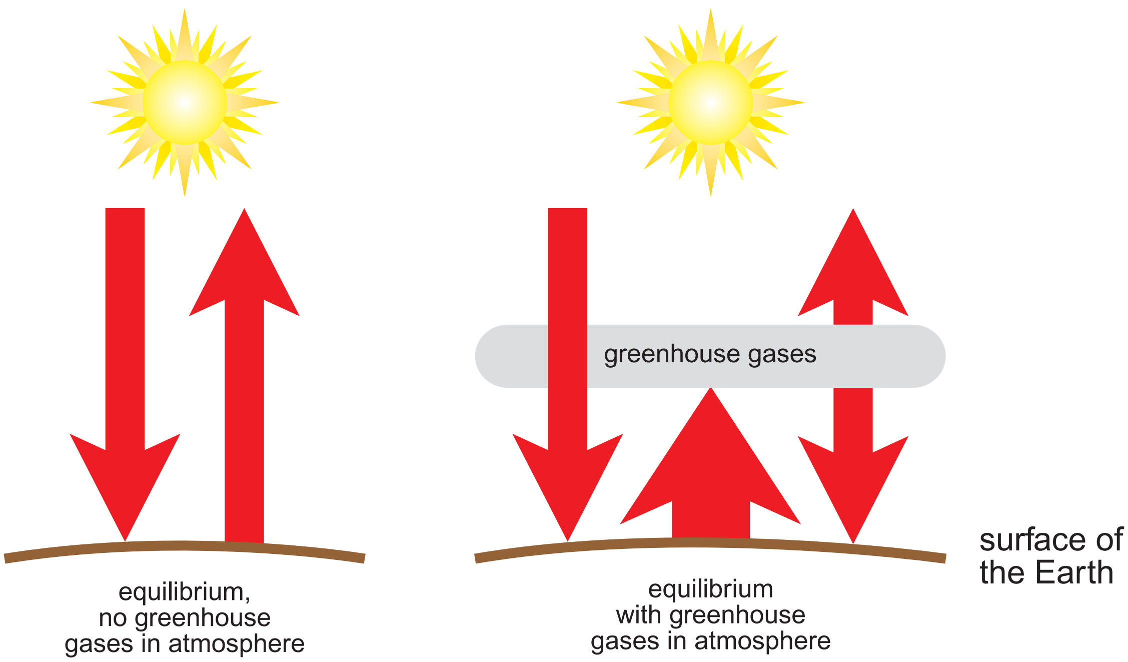
2.3 Equilibrium is reached when the temperature of the atmosphere is sufficiently high that heat radiated out to space balances the radiation the Earth absorbs from the sun. Because of the greenhouse effect, the average temperature on the surface of the Earth is more than 30°C higher than it would otherwise be. Without the greenhouse effect, life as we know it would not be possible.

2.4 The concentration of greenhouse gases in the atmosphere has risen steadily over the last 250 years. In the 20th century the global mean temperature of the Earth's surface has risen by about 0.6°C,[3] and analysis of measurements over a recent period of 18 months suggests it is now rising at a rate of up to 3°C in 100 years.[4] Scientific analysis suggests that the increased concentration of greenhouse gases resulting from human activities has enhanced the natural greenhouse effect, and that this in turn has largely caused the global warming which has been observed.[5] That is the basis for concern that the climate is changing as a result of human activities.

2.5 The most important natural greenhouse gases are water vapour, carbon dioxide and methane. *Water vapour* makes the largest contribution to the natural greenhouse effect. There is a vast store of water in the oceans, and large amounts of water move naturally between the

Figure 2-I

How the greenhouse effect raises the Earth's temperature



oceans and the atmosphere. There is negligible direct human impact on the amount of water in the atmosphere. If on the other hand the atmosphere becomes warmer for some other reason, it can contain more water vapour. That enhances the greenhouse effect and causes even more warming. This is an example of positive feedback in the climate system.

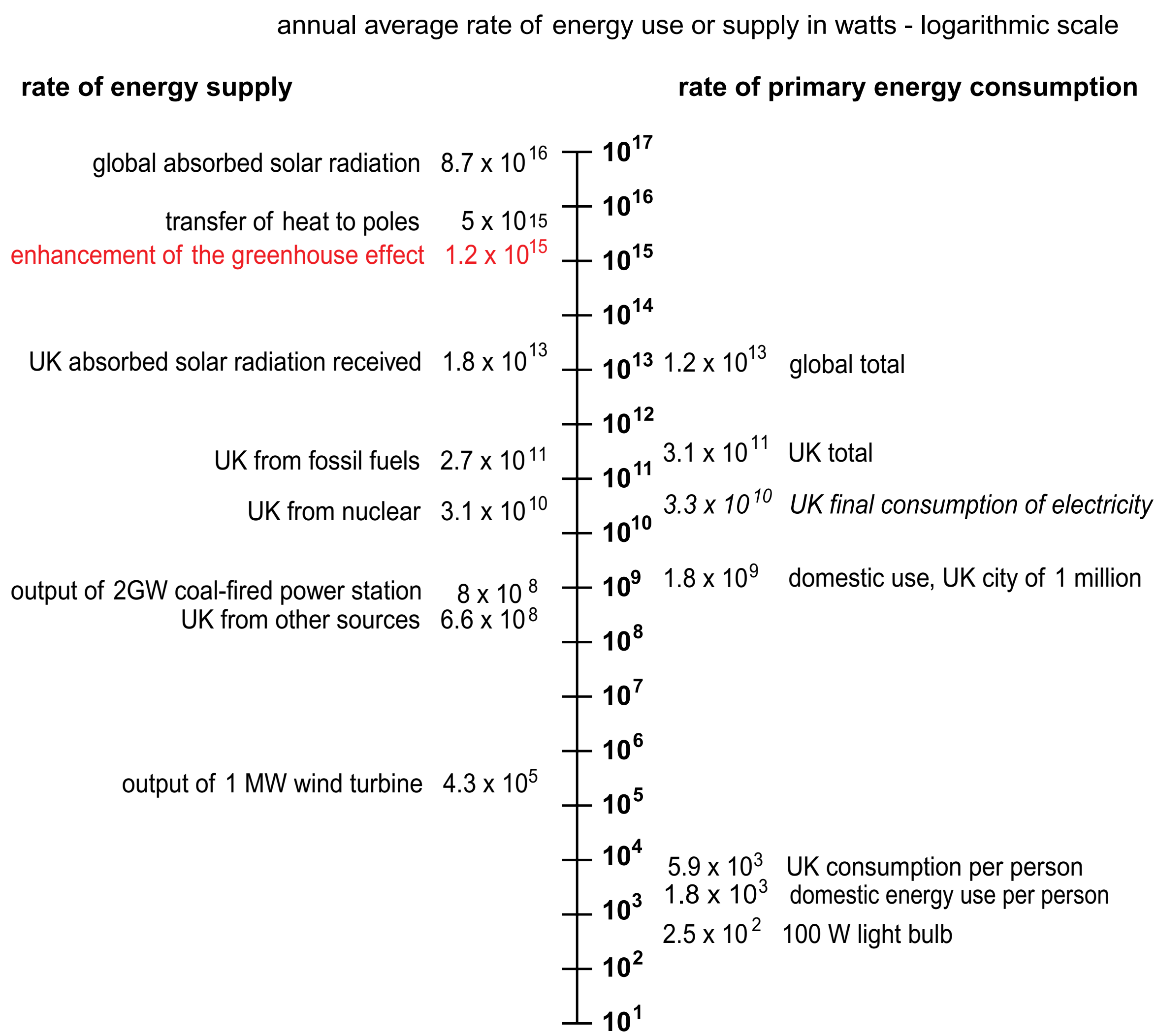
2.6 Another way in which water vapour influences the greenhouse effect is that it condenses to form clouds. By not allowing solar radiation through, clouds serve to cool the Earth's surface: conversely they serve to warm the surface by preventing heat from being lost directly to space. The cooling effect is dominant for low-level clouds and the warming effect for high-level clouds. One of the major difficulties in modelling climate is to simulate changes in cloud cover at different altitudes with sufficient accuracy to provide a reliable estimate of the net change in the heating of the Earth's surface.

2.7 *Carbon dioxide* is the second most important natural greenhouse gas, and the most important in terms of human impact on the atmosphere. As shown below, its concentration in the atmosphere can vary naturally; but following the end of the last glacial period it was approximately constant for 10,000 years at about 270-280 parts per million by volume (ppmv).[6] Over the last 250 years, as industrialisation has taken place, the concentration has risen to about 370 ppmv.[7] It is now increasing by 0.4% a year on average. Two-thirds of the current enhancement in the greenhouse effect is estimated to be due to this increased concentration of carbon dioxide.[8] Nearly four-fifths of the extra carbon dioxide entering the atmosphere since 1750 is estimated to have come from burning fossil fuels.[9] A small amount has come from calcium carbonate used to manufacture cement[10] and the rest is the result of deforestation and other changes in land use.

2.8 The concentration of *methane* has also been increased by human activities, more than doubling over the last 200 years. It is thought to contribute about one-fifth of the current enhancement in the greenhouse effect.[11] The role of individual sources is uncertain. A large proportion of methane emissions are the result of land use, including those from wetlands, paddy fields and termites. About 28% are thought to be associated with fossil fuel extraction (through leakage from coal mines, gas pipelines and oil wells); 7-8% come from landfill sites and comparable amounts from sewage treatment and from animal wastes.[12] The significance for global warming of greenhouse gases other than carbon dioxide is considered further in boxes 2B and 2C below.

2.9 Figure 2-II shows the relative magnitudes of some natural energy flows, various forms of electricity generation, and human consumption of primary energy both in the UK and globally. It shows why enhancement of the greenhouse effect (in red type) is a matter of such concern. The rate at which primary energy is consumed worldwide by human activity is 10,000 times less than the rate at which energy reaches the Earth from the sun. It is about 1,000 times less than the rate at which the atmosphere and oceans transfer energy from low to high latitudes (for example through the northward movement of warm water in the North Atlantic). The waste heat passing into the atmosphere as a result of human energy consumption can therefore be regarded as having a negligible direct effect on the global climate system. The increase in the

Figure 2-II
Global and UK energy sources and consumption



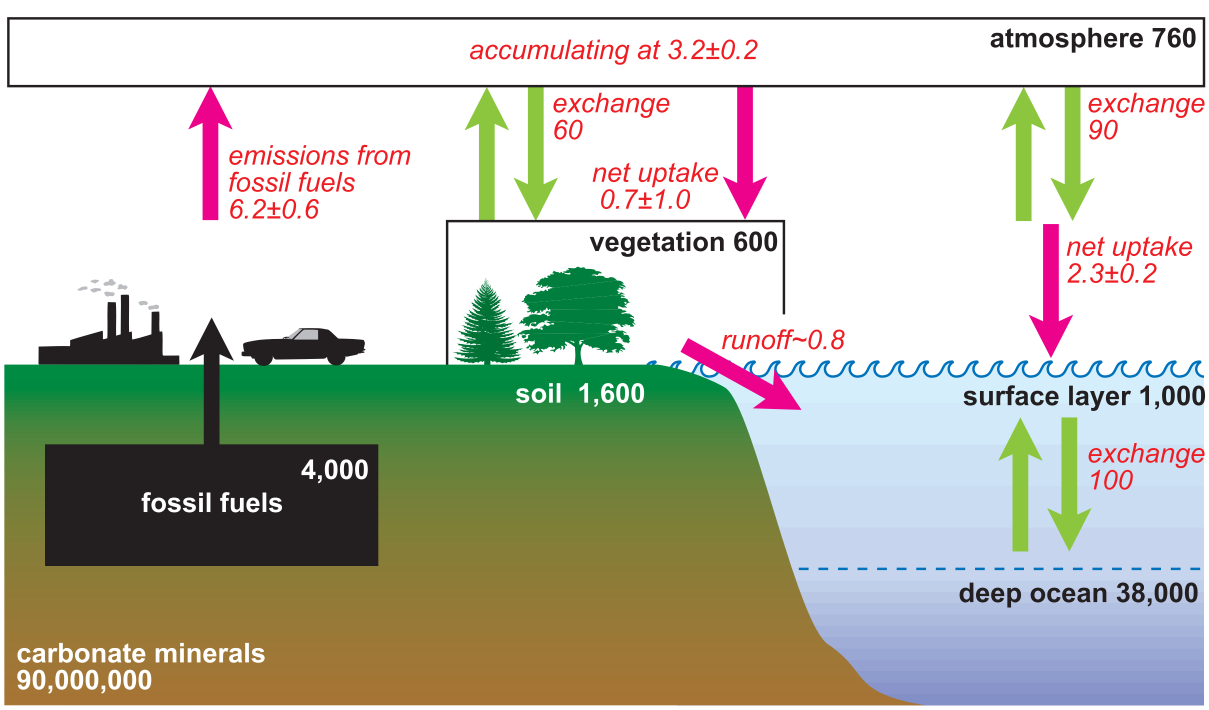
concentration of greenhouse gases, on the other hand, is much more significant in its potential impact. If the same quantities of gases had suddenly been added to the atmosphere, the result would have been a massive imbalance in the rates at which energy is received and lost by the Earth; the magnitude of that imbalance is only four times smaller than the rate at which energy is transferred naturally towards the poles, and is therefore very significant in terms of the climate system. Further large enhancements of the greenhouse effect are in prospect if carbon dioxide emissions continue to rise.

The global carbon cycle

2.10 In the absence of human intervention, the concentration of carbon dioxide in the atmosphere is the outcome of a natural cycle, illustrated in figure 2-III.[13] Assessing the effects of burning fossil fuels involves understanding how that cycle operates. The gross flows (green arrows) are much larger than the net flows (red arrows). Rocks, organic material and the oceans continuously release carbon into the atmosphere in the form of carbon dioxide and continuously re-absorb it. If the rate of re-absorption balances the rate of release, a dynamic equilibrium is maintained and the concentration of carbon dioxide in the atmosphere remains approximately constant. That was the situation for 10,000 years prior to industrialisation.

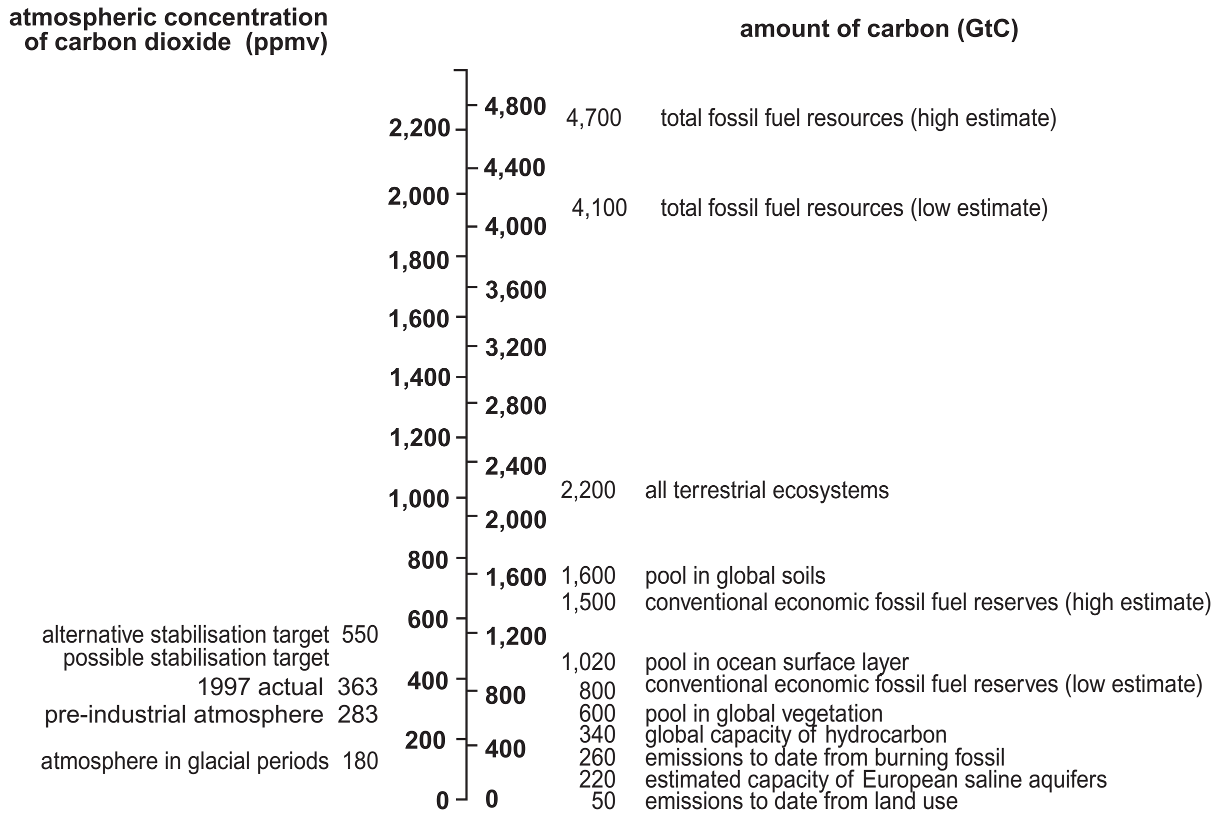
2.11 Figure 2-III also indicates the sizes of the various natural pools of carbon; figure 2-IV compares these with the amounts of carbon represented by specified concentrations of carbon dioxide in the atmosphere. Worldwide, vegetation is estimated to contain 600 gigatonnes of carbon (GtC), which is also roughly the amount that was in the atmosphere before

Figure 2-III
Global carbon cycle



figures in **bold** type show estimated size of pools
figures in *italics* show estimated average annual flows

Figure 2-IV
Amounts of carbon in atmosphere and pools



Following common practice, amounts of both carbon and carbon dioxide are expressed in this report in terms of tonnes of carbon.The left-hand scale shows, for the amounts of carbon indicated on the right-hand side of the diagram, what they would represent as an addition to the concentration of carbon dioxide in the atmosphere if they were to be released into the atmosphere instantaneously in the form of carbon dioxide.

industrialisation began. The organic matter in soils represents a larger pool of carbon (1600 GtC), much of it in peats or in forest or wetland soils (see table 3.1). Enormous quantities of carbon are locked up in carbonate minerals. Otherwise the largest pool of carbon is in the oceans, an estimated 1000 GtC in the surface layer and 38,000 GtC in deeper waters.

2.12 The natural carbon cycle operates on different time-scales. Over years and decades, respiration by animals and plants and the natural burning and decay of vegetation release carbon dioxide into the atmosphere, while growth of vegetation removes it. The residence time of carbon dioxide dissolved in the surface layer of the oceans and taken up by living organisms can also be short. Carbon may remain in soils for a century, and in peat deposits for millennia. Over tens of millions of years, the dead remains of organisms which have taken up carbon are buried in accumulating sediments, mostly in the oceans; carbonate rocks are formed; and the carbon they contain is eventually released by erosion.

2.13 Over the last 250 years the mining and burning of fossil fuels has removed 260 GtC from the slow part of the natural cycle and transferred it rapidly to the atmosphere.[14] Carbon has not been removed from the atmosphere at a correspondingly rapid rate because the natural pools, or *sinks,* have not been able to absorb it in such quantities over such a relatively short period.

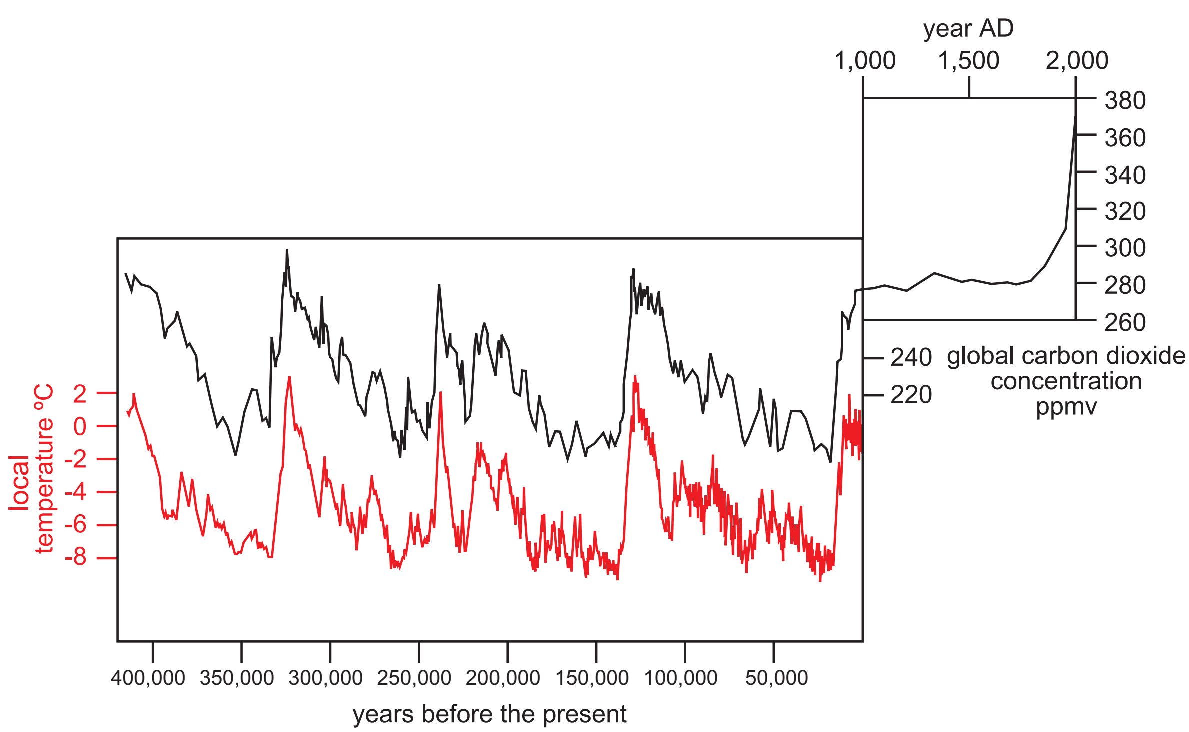
The oceans are estimated to have absorbed 140 GtC;[15] but terrestrial ecosystems have been the source of a further 50 GtC, mainly as a result of forest clearance and other changes in land use. The net addition since 1750 to the amount of carbon dioxide in the atmosphere is therefore estimated to have been 170 GtC.[16]

Natural variations

2.14 Figure 2-V shows variations in the carbon cycle that have occurred naturally over the last 400,000 years (in black) and how these related to changes in temperature (in red); box 2A describes the nature of the evidence, which comes from the Greenland and Antarctic ice sheets. During relatively warm periods (similar to the climate over the last 10,000 years) the concentration of carbon dioxide in the atmosphere was, as in the pre-industrial period, about 270-280 ppmv; during the coldest parts of glacial periods it was significantly lower, about 180-190 ppmv.

Figure 2-V

Carbon dioxide concentration and temperature: evidence from ice cores



2.15 The shifts between these two concentrations reflect changes in the carbon pools shown in figure 2-IV. The oceans and terrestrial ecosystems can act either as net sources of carbon or net sinks. During periods when the Earth is cooling, cold water upwelling in the equatorial oceans absorbs carbon dioxide from the atmosphere; its concentration in the atmosphere therefore falls. During periods when the Earth is heating up, the reverse effect occurs: the equatorial oceans become a net source of carbon and the concentration in the atmosphere increases. During these cycles of cooling and warming, the amounts of carbon stored in terrestrial ecosystems also increase and decrease, but there is no consensus as yet on when terrestrial ecosystems act as a sink and when as a source (see appendix D, D.26-D.29).

2.16 All the significant changes in temperature shown in figure 2-V were associated with a significant change in the concentration of carbon dioxide in the atmosphere. The precise causation is more difficult to determine. The current view is that small cyclical changes in the solar radiation reaching the Earth are amplified by positive feedback between surface temperature and carbon dioxide concentration (see box 2A).

BOX 2A **EVIDENCE OF NATURAL VARIATIONS**

The centres of the Greenland and Antarctic ice sheets are stratified layers providing a continuous record over half a million years. For at least the last 30,000 years annual layers can be identified. The isotopic composition of the ice enables a reliable estimate to be made of the air temperature in that area at the time when precipitation caused the ice to form. Gas bubbles within the ice are thought to provide a reliable record of the concentration of carbon dioxide in the global atmosphere shortly after the ice formed.

Figure 2-V shows the record in cores taken from the Vostok ice sheet in Antarctica of carbon dioxide concentration (in black) and temperature (in red) over the last 400,000 years.[17] The inset shows the concentration of carbon dioxide in the global atmosphere over the last 1,000 years; it is based on analysis of gas bubbles in stratified layers in glaciers, and for more recent years on direct measurements.

Changes in the carbon dioxide concentration in the atmosphere have been closely correlated with changes in temperature. Does a rise in temperature cause carbon dioxide to be released from the oceans, thus increasing the concentration in the atmosphere, or does an increased concentration of carbon dioxide cause temperature to rise? It is known that both processes occur. Equally, it is known that warm tropical oceans release carbon dioxide, whilst cold, polar oceans absorb carbon dioxide. The correlation shown in figure 2-V is probably forced ultimately by changes in the distribution of the solar radiation received, especially by the polar regions, caused by cyclical changes in the Earth's orbit. If changes in solar radiation raise the temperature of the Earth's surface, there is a net release of carbon dioxide from the oceans, the concentration in the atmosphere increases, and further warming occurs because of the greenhouse effect; that in turn releases more carbon dioxide, and so on in a positive feedback. The reverse process occurs if changes in solar radiation result in a cooling of the Earth's surface. Complicating factors include the expansion and contraction of ice sheets (which absorb less solar radiation) and the factors governing the rate at which carbon moves into and out of the deep oceans (3.12, 3.24).

2.17 The present concentration of carbon dioxide in the atmosphere, about 370 ppmv,[18] is well outside the range recorded over the last half million years. To find anything comparable means going back 3 million years to the Pliocene period. The concentration is thought to have been higher than now (around 500 ppmv, double the pre-industrial level) in the Eocene period, between 35 and 57 million years ago. Modelling suggests that concentrations of 1,000 ppmv were last present some 70 million years ago, in the Late Cretaceous period, towards the end of the age of the dinosaurs.[19] At that time, global mean surface temperature is thought to have been some 6°C higher than today.

2.18 The present concentration of carbon dioxide in the atmosphere is bound to increase further because emissions are continuing to rise, and because carbon dioxide remains in the atmosphere for 50-200 years.[20] As we show below, models indicate that that this change in concentration will lead to significant changes in climate. There is no precedent in recent geological history to help us understand precisely what consequences will follow. Nor can we use analogies from the more distant past to show what changes in climate will result, for two reasons. Many other conditions, such as the strength of the sun and the positions of the continents, were radically different at that time; and the speed at which the carbon dioxide concentration is changing appears to be unparalleled in geological history.

Possible scenarios

2.19 Assessing the seriousness of the challenge posed by climate change involves several stages. First, projections have to be made of the amounts of greenhouse gases that will be emitted into the atmosphere in future. For carbon dioxide those projections have to take into account, not only emissions from burning fossil fuels, but also any other increased amounts entering the atmosphere as a result of human activities (for example forest clearance). To determine what effects emissions will have on the concentrations in the atmosphere, estimates have to be made of the amounts that will be removed by the global carbon cycle and other natural chemical cycles. Next, the likely consequences for the climate have to be predicted. Finally, the impacts of the changing climate have to be assessed. Each stage uses mathematical models. Predicting changes in climate involves constructing and running complex models, requiring use of the largest and fastest computers, in order to represent the behaviour of the atmosphere, oceans and land surface and the relevant interactions between them.

2.20 Some of the main scenarios for future emissions used by IPCC are described in box 2B. Figure 2-VI shows some of those included in its Second Assessment in 1995. Scenario IS92a (the black line in figure 2-VI) was regarded as 'a reasonable central case projection for global emissions';[21] it assumes there will be a considerable improvement globally in the efficiency of energy use and a very big increase in the amounts of energy obtained from sources other than fossil fuels,[22] but that carbon dioxide emissions will nevertheless increase rapidly. On this scenario, the carbon dioxide concentration in the atmosphere in 2100 would be more than 700 ppmv, roughly double the present level and more than two and a half times the pre-industrial concentration. Models run by the Hadley Centre for Climate Prediction and Research (part of the Meteorological Office) indicate that the outcome by 2100 would be a global mean surface temperature 4.3°C above the pre-industrial level.[23]

2.21 Even if emissions from burning of fossil fuels had simply continued at the 1990 level, the concentration of carbon dioxide in the atmosphere would have increased to 500 ppmv by 2100,[24] with further increases thereafter. All the scenarios described in box 2B assume that the continuing growth in emissions cannot immediately be halted and they will continue rising for some years. The other scenarios in figure 2-VI were included in IPCC's 1995 assessment to show how hypothetical reductions in emissions might eventually stabilise the carbon dioxide concentration at 450 ppmv (green), 550 ppmv (blue) or 750 ppmv (red). These stabilisation scenarios provide an important basis for considering what form the world community's response to the problem of climate change should take, the issue we consider in chapter 4. Modelling indicates that the increase in global mean surface temperature by 2100 would be limited to 2.8°C under the 750 ppmv scenario and 2.3°C under the 550 ppmv scenario. The temperature increases in 2200 would be 3.9°C and 2.9°C respectively, with only small increases after that date.[25] The three solid lines in figure 2-VI assumed adjustment would begin in the mid-1990s. The relevant scenarios now therefore are the broken lines, which show adjustment beginning from later dates and emissions dropping more quickly.

2.22 In its Third Assessment IPCC is examining a range of scenarios for emissions up to 2100, based on alternative storylines for the world economy, population growth, development and application of technology, and social and political behaviour. The graphs in figure 2-VII show four scenarios for carbon dioxide emissions from burning fossil fuels, extended from 2100 to 2300 on the basis described in box 2B. Also shown are the consequences the projected emissions would have for carbon dioxide concentration, according to a simplified model developed at the

Hadley Centre. To highlight the main features of these new scenarios, as extended for the purposes of this report, we call them 'total exhaustion' (that is, exhaustion of the total resource base of fossil fuels), 'partial exhaustion', 'late adjustment' and 'earlier adjustment'.

2.23 In the *total exhaustion scenario* (red in figure 2-VII) there is a continuing large growth in emissions from burning fossil fuels. By 2100 use of fossil fuels on this scale would exhaust conventional economic reserves of such fuels, even at the higher end of the range of estimates of such reserves (appendix D, D.5); by 2200 the total resource base of such fuels would be exhausted on current estimates. By 2100 the concentration of carbon dioxide in the atmosphere would be about three times, and by 2200 about six times, the pre-industrial level. It would peak towards the end of the 23rd century at about 2,100 ppmv. In the *partial exhaustion scenario* (blue) the growth in carbon dioxide emissions is much less rapid (and less rapid than in the previous IS92a scenario); but, because it continues unchecked throughout the 21st century, conventional economic fossil fuel reserves would run out by about 2100 at the middle of the range of estimates. As in the previous scenario, the concentration of carbon dioxide in the atmosphere would peak in the latter part of the 23rd century, but would be about half as high, at more than three and a half times the pre-industrial level.

2.24 The other two scenarios shown in figure 2-VII both envisage that emissions from burning fossil fuels will be on a downward path well before the end of the 21st century, but differ in the timing and nature of the adjustment. In the *late adjustment scenario* (orange) global emissions over the next 50 years are close to those in the total exhaustion scenario, but then decrease rapidly until 2200. By that time the carbon dioxide concentration has become nearly constant at about 800 ppmv, nearly three times the pre-industrial level. In the *earlier adjustment scenario* (green) the rise in carbon dioxide emissions slows much more quickly. At their peak in 2060 global emissions are two-thirds as high again as today. The concentration in the atmosphere rises to nearly double the pre-industrial level by 2100 and then becomes nearly constant at about 600 ppmv.

2.25 The alternative policies implied by the four scenarios exert their effects over a very long period (see the lower two graphs in figure 2-VII; these predictions for temperature and sea level include a contribution from other greenhouse gases, as explained in box 2C). In 2100 the increases in global mean surface temperature above the pre-industrial level range from 4.5°C under the total exhaustion scenario to 3.2°C under the earlier adjustment scenario; taking today as the starting point, the predicted increases are about 1°C smaller. By 2200 the range is much wider, from 7.7°C to 4°C. There are considerable time-lags in the climate system: temperatures continue to rise long after emissions have started to decline, mainly because of the slowness of natural cycles (2.12, 2.13). Thus, although emissions in the late adjustment scenario drop below those in the partial exhaustion scenario by 2100, it is not until 60 years later that the increase in temperature is less; under both adjustment scenarios global mean surface temperature is still rising slowly in 2300, by which time it is about 4.9°C and 4.2°C, respectively, above the pre-industrial level.

2.26 Assessments of climate change have not usually taken into account interactions between the different stages in the calculations (2.19), for example how changes in climate would affect the rate at which greenhouse gases are removed from the atmosphere by natural processes. Recent work at the Hadley Centre has, for the first time, coupled a model of the land and ocean carbon cycle into a full climate model in order to make predictions for the next 100 years. Preliminary results suggest that in the second half of the century the carbon dioxide concentration in the atmosphere will rise more rapidly than in standard climate predictions, partly because some tropical rain forests will be reduced in area and partly because higher

Figure 2-VI
IPCC 1995 stabilisation scenarios

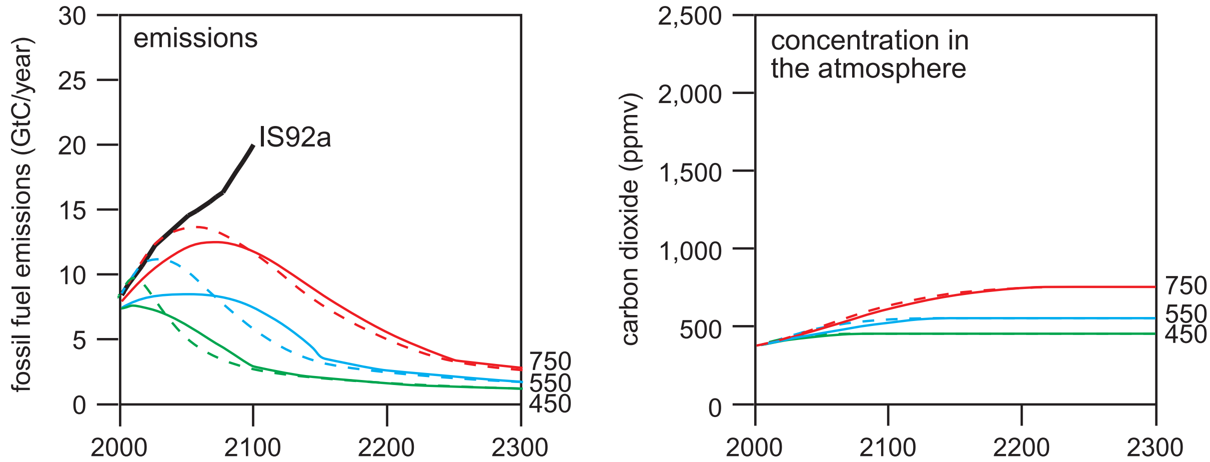
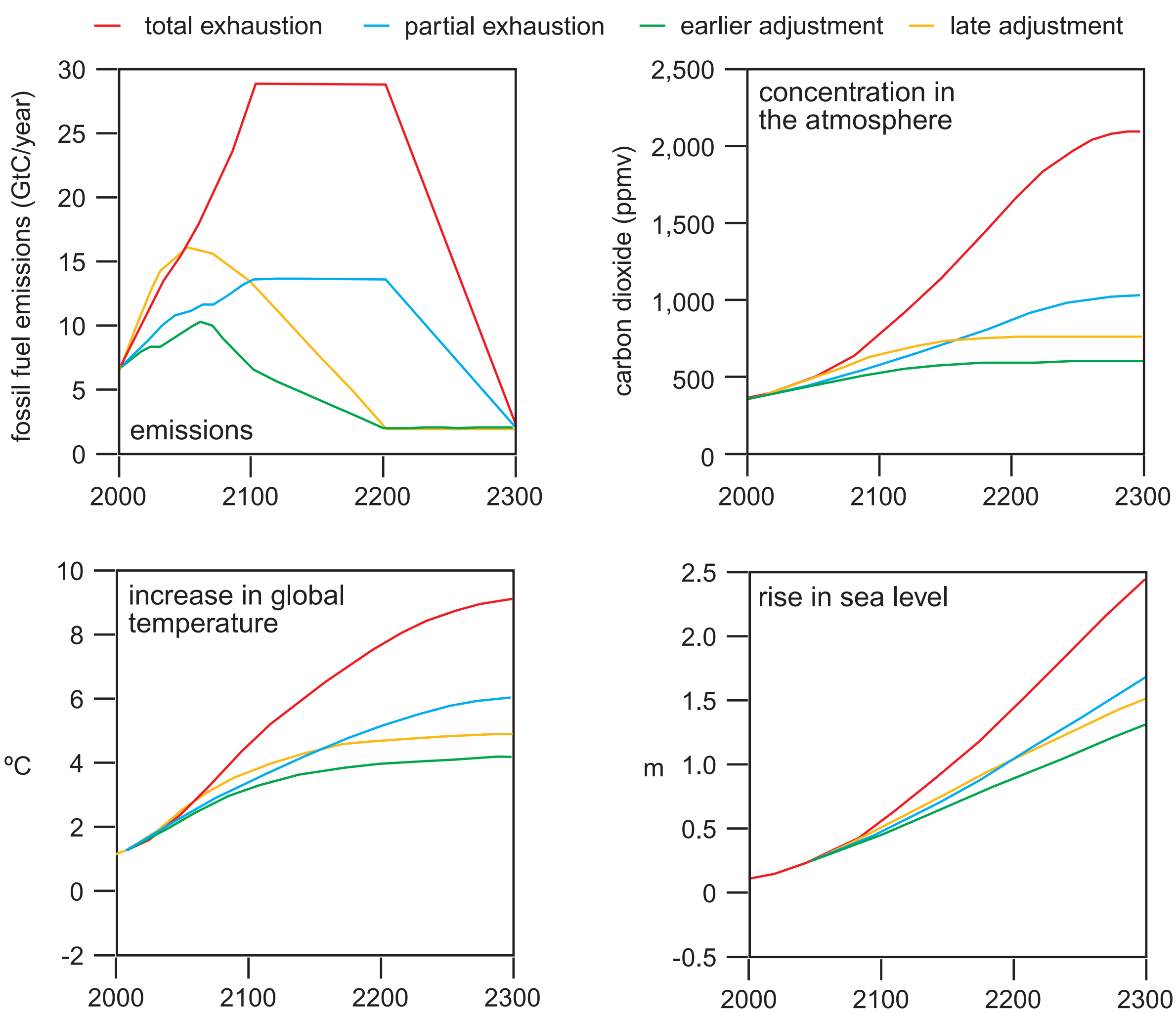


Figure 2-VII
Four scenarios for carbon dioxide emissions and their effects



BOX 2B **SCENARIOS FOR EMISSIONS**

Emission scenarios are projections of anthropogenic emissions of greenhouse gases based on assumptions about future trends in key determinants such as population, economic growth, energy supplies, technological change, land use and emission control policies. In 1992 IPCC developed a set of six emission scenarios. Emissions of greenhouse gases other than carbon dioxide were taken into account, but it was thought likely that increased concentrations of those gases would be approximately balanced at global level by the cooling effect of an increase in small particles in the atmosphere, also due to human activities. Future quantities of small particles and their cooling effect are now thought to have been over-estimated.

One of IPCC's 1992 scenarios, IS92a, which has been much used subsequently and is shown in figure 2-VI, is usually referred to as 'business-as-usual', although that name is somewhat misleading (2.20). Also shown are three pairs of scenarios constructed by IPCC in 1995, in which carbon dioxide emissions increase initially but then fall rapidly. According to the model used then, these pairs of scenarios would stabilise the concentration of carbon dioxide in the atmosphere at 450, 550 and 750 ppmv, respectively. They have been used extensively in policy discussions. To a first approximation, the eventual concentration in the atmosphere depends on cumulative emissions rather than the exact path followed. These stabilisation scenarios should therefore be viewed as examples of families of curves that would achieve almost the same results.

In 1996 IPCC decided to develop a new set of emission scenarios, using four storylines for world economic, social, political and technological development up to 2100. Figure 2-VII shows four emission scenarios for carbon dioxide representative of these storylines, with simple extensions to 2300 which we have made in order to analyse longer-term implications for climate and sea level.

In the two *adjustment scenarios* (2.24) emissions are assumed to fall by 2200 to a sufficiently low level that the concentration of carbon dioxide in the atmosphere would be roughly stabilised. A main factor taken into account in extending the other two scenarios (2.23) is estimates of fossil fuel resources. In the *exhaustion scenarios* emissions are assumed to continue at a constant rate from 2100 to 2200. In the *total exhaustion scenario* the total fossil fuel resource base (excluding methane hydrates) would have been used up by 2200, even at the upper bound of estimates (appendix D, D.5). In the *partial exhaustion scenario* burning of fossil fuels up to 2200 would have used up half that resource base, on the lower bound of estimates. In both scenarios, for simplicity, emissions fall linearly to a very low level by 2300; if they were reduced directly to this low level at 2200, the effects on temperature and sea level would be little different to those shown in figure 2-VII.

temperatures may increase emissions from soils. Thus the predictions shown in figure 2-VII, made with uncoupled models, may well be under-estimates.

Nature and consequences of climate change

2.27 Apart from increases in global mean surface temperature, it is predictions about rises in sea level that can be made with most confidence. As the water in the oceans becomes warmer, it expands. It takes a very long time, however, for warming of the ocean surface to be transmitted in full to the deep ocean: emissions of carbon dioxide over coming decades will produce rises in sea level for many centuries.

2.28 In the 20th century the rise in sea level indicated by Hadley Centre models, about 0.13 m, is within the range of observed changes. Calculations based on IPCC's 1995 scenarios predict a future rise in sea level of about 0.7 m a century (IS92a), 0.4 m (stabilisation at 750 ppmv) or 0.3 m (stabilisation at 550 ppmv). This is broadly consistent with the predictions of the new scenarios shown in figure 2-VII. By 2200 sea level has risen by 0.9-1.4 m. In the 23rd century it

BOX 2C	OTHER GREENHOUSE GASES

The United Nations Framework Convention on Climate Change defines greenhouse gases as 'those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation'.[26] Carbon dioxide is estimated to have contributed two-thirds of the current enhancement in the greenhouse effect (2.7), but other greenhouse gases directly affected by human activities make a larger contribution to the greenhouse effect in relation to the amounts in which they are present in the atmosphere. Some of them exist naturally but are now present at higher concentrations, such as nitrous oxide and ozone (in the lower part of the atmosphere). Others are synthetic, for example halocarbons such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and related bromine compounds.

The other greenhouse gases covered by the Kyoto Protocol (4.8) are methane, nitrous oxide, HFCs, perfluorocarbons and sulphur hexafluoride.

The use of CFCs is being phased out because of another effect they have, which is to deplete the ozone layer in the stratosphere (4.57); unfortunately HFCs, which were introduced as substitutes, are themselves extremely powerful greenhouse gases, with a global warming potential many thousands of times larger than the same mass of carbon dioxide.

The concentration of other greenhouse gases in the atmosphere is sometimes expressed as the concentration of carbon dioxide that would have a similar effect globally (the equivalent quantity varies according to the concentration of carbon dioxide present). Until recently, most climate models and many scenarios have used this approach to provide a single measure of the effects of all greenhouse gases directly affected by human activities.

In the four scenarios shown in figure 2-VII emissions of greenhouse gases other than carbon dioxide increase in accordance with IPCC's storylines up to 2100, and are then assumed to continue at a constant rate until 2300.

rises by a further 0.4-1.0 m, even though emissions under all four scenarios are by then falling to a very low level. The new scenarios therefore predict a further rise in sea level between now and 2300 ranging from 1.2 m (earlier adjustment) to 2.3 m (total exhaustion).

2.29 A rise in sea level on that scale would submerge much of the territory of some island nations. It would accelerate the erosion of coasts made of soft rocks and threaten many low-lying hinterlands which are protected at present by coral reefs or mangroves. Deltas such as those of the Nile and the Ganges/Brahmaputra in Bangladesh would be especially at risk. So would coral atolls; the rates at which sea level is predicted to rise may outstrip the growth capacity of corals and they are liable to be damaged by the higher temperature of the sea.[27] The rise in sea level predicted under the IPCC IS92a scenario has been estimated to increase the number of people in the world affected by coastal flooding from 13 million each year to 94 million each year by the 2080s, unless there were to be large-scale migration away from threatened areas. Four-fifths of the people affected would be in south and south-east Asia.[28]

2.30 One possibility frequently discussed is that over several hundred years sea level might rise by an additional 5-8 m because of the collapse of the West Antarctic ice sheet. This ice sheet is grounded on islands slightly below sea level and it has been suggested that it may become unstable as a result of increases in temperatures and sea level. The balance of opinion appears to be against that occurring, but it remains a possibility.[29] If it occurred, the rapidity and extent of the rise in sea level would indeed be catastrophic.

2.31 Climate models show the average surface temperature on land increasing half as fast again as the global mean, and twice as fast in northern high latitudes.[30] Thus, by 2100, an increase in the pre-industrial global mean surface temperature ranging from 2.3°C (550 ppmv stabilisation scenario) to 4.5°C (total exhaustion scenario) implies an increase on land in northern high latitudes of the order of 4-9°C. For precipitation, most models predict increases globally, but especially in winter in high latitudes. They also predict more frequent and intense floods and droughts, because the hydrological cycle will become more intense.

2.32 Beyond these very broad statements, it is difficult to make confident predictions about the changes in regional climates, or about the occurrence of extreme events such as storms. Most impacts of climate change, apart from sea level rise, will be dependent on such local detail. The difficulties of prediction stem partly from current limitations in understanding, partly from limits on computational power, and partly from the inherent variability of weather and climate. There is less confidence as the region of interest becomes smaller and the time period becomes shorter. Precipitation is more difficult to predict than temperature. Despite the problems of making predictions for relatively small areas, attempts have been made to assess the likely impacts on the UK, and the conclusions are summarised in box 2D.

2.33 A change in the average surface temperature in northern high latitudes which would be of the order of 9°C by 2100 at the upper end of the range is more dramatic than it may look at first sight. It is comparable with the temperature difference on the northern continents between the coldest part of the last glacial period, 18,000 years ago, and the beginning of the interglacial period, 10,000 years ago. That historic change in temperature, which was associated with enormous changes in the environment, took place over a long period. The temperature changes indicated by the emission scenarios are of a similar magnitude but take place at ten to fifty times the speed. Recent studies suggest that smaller changes in climate have sometimes occurred rapidly, over centuries or decades. But this combination of magnitude and rate of change would exceed anything species and ecosystems have experienced in the last half million years.

2.34 There are also uncertainties about whether abrupt changes in climate might occur. For example some models predict that the North Atlantic ocean circulation system, which transports heat from the sub-tropics towards Europe, might shut down. The result would be that western Europe would not warm up so much, and might even become cooler than now. Abrupt changes are typical of non-linear systems, and climate models may not be very accurate in predicting them.

2.35 Despite the uncertainties about effects at regional level, an attempt has been made to assess the effects the IS92a emission scenario shown in figure 2-VI would have on agriculture and natural ecosystems.[35] The change in climate and the higher concentration of carbon dioxide might increase cereal yields at high and mid latitudes. On the other hand yields would be reduced in Africa, the Middle East and India. There could be a similar disparity in the case of natural ecosystems: there might be considerable additional forest growth in North America, northern Asia and China, but a large-scale die-back of tropical forests and increasing desertification, especially in South America and southern Africa. Other nations and communities will face changes in the environment that will force them to make drastic alterations in their ways of life and in land use and other practices. In some parts of the world millions of people might become environmental refugees, with widespread suffering, economic disruption, and consequent social and political instability.

BOX 2D	IMPACTS OF CLIMATE CHANGE ON THE UK

Current global climate models cannot reliably predict changes in the climate of the UK or any other individual country.

One change that can be predicted with confidence, because it will be worldwide, is the rise in sea level. Rises of the magnitude shown in figure 2-VII will have a significant effect on coastal areas of the UK. Erosion will become more severe, especially on the long stretches of the south and east coasts composed of chalk, clay and other soft rocks. On the east coast sea level is already rising because of slow sinking of the Earth's crust. More than half the grade 1 agricultural land in the UK lies beneath the 5 m contour, and much of it lies behind vulnerable eastern coasts. Areas closest to the sea may become contaminated with salt through underground intrusion of sea water; unless such land is protected, its productivity will decrease drastically.[31] Major cities, notably London, lie on east coast estuaries and are already at risk of being flooded by tidal surges. A combination of new estuarine and coastal defences, including tidal barriers, and managed retreat (abandoning some land to the sea) is likely to be necessary.

Assessments of other effects must be regarded, in general, as illustrative scenarios.[32] On the assumption that the rate of warming in the UK will be similar to the global rate, a medium to high projection of climate change implies that by the 2080s nearly every year will be warmer than 1997, which was the third warmest year ever recorded in the UK and 1.1°C warmer than the average between 1961 and 1990.

Increased frequency of climate extremes, such as droughts and floods, would have some of the most noticeable impacts. Summer rainfall 50% below the current average is likely to occur once a decade, as against once a century under the present climate.[33] If, as some models suggest, very heavy precipitation becomes more frequent, flash floods would become more prevalent, with an increased threat to towns and villages built on flood plains.

Predictions about what will happen in different parts of the UK are subject to even greater uncertainty. A study for Scotland has suggested that rainfall and severe gales would increase, with an increased risk of flooding.[34] One scenario suggests that the south east of England could experience the greatest warming and significantly drier summers. If this were to happen, water supplies would come under stress, not least because lower summer rainfall would increase the demand for farm irrigation.

Warming would tend to increase agricultural and forestry yields, but also favour some pests and diseases. Changes in temperature and rainfall would alter the distribution of wild species; a 1°C rise in average temperature displaces the limits of tolerance of a species 300 km northwards, or 150 m vertically. There would be losses and gains: the species lost would be likely to include arctic-alpine plants and birds that maintain small populations on the highest hills, while the gains would be especially in the south east (assuming suitable habitats exist). An increased frequency of climate extremes would be significant for plant and animal species, which may survive one season, but not a sequence of extreme events. In addition to the damage to coastal nature reserves from the rise in sea level, some small inland nature reserves might cease to provide habitats for the species for which they were created.

Although the speculative dimension of scenarios makes planning difficult, the potential impact of climate change needs to be taken into account in long-term strategies for land use planning, water resource management, coastal and flood defences, agriculture, forestry, countryside recreation and nature conservation.

Facing the issues

2.36 We received a few submissions,[36] including one from a major oil company, arguing that the scientific evidence about climate change[37] is too uncertain to provide an adequate basis for changes in policies. By signing and ratifying the United Nations Framework Convention on Climate Change (UNFCCC), governments have signalled their rejection of such views (4.5).

There is a broad consensus among leading climate scientists that emissions from human activities are enhancing the natural greenhouse effect, that this is already having a discernible effect on climate, and that the ultimate effect will be much larger. Predictions of changes in global mean surface temperature, and in sea level, can be made with some confidence. Considerable uncertainties remain about the nature and extent of other effects, but that is an inescapable feature of environmental science.[38] By the time the effects of human activities on the global climate are clear and unambiguous it would be too late to take preventive measures. There is a very strong likelihood that the overall impact will be seriously damaging. There is also the possibility that abrupt changes in the climate system might be triggered and have even more dramatic impacts.

2.37 Countering the threat of climate change means controlling the combined effect from increases in the concentrations of all greenhouse gases. Although carbon dioxide is the most important greenhouse gas in terms of human impact on the atmosphere, increases since industrialisation in the concentrations of other greenhouse gases are currently equivalent in effect to a further increase of 50 ppmv in the concentration of carbon dioxide (see box 2C). Moreover the exploration of alternative scenarios has to take into account further increases that may occur in emissions of those gases. The four new scenarios for carbon dioxide emissions shown in figure 2-VII assume emissions of other gases will also increase. In terms of predicted effects therefore IPCC's 1995 scenario for stabilisation at 750 ppmv of carbon dioxide shown in figure 2-VI (based on the view that there would not be any further net addition to the greenhouse effect from other gases) is broadly equivalent to the earlier adjustment scenario shown in figure 2-VII, which eventually results in a nearly constant carbon dioxide concentration of about 600 ppmv. In terms of temperature, both eventually achieve equilibrium at a global mean surface temperature about 4°C above the pre-industrial level.[39] Similarly, because it did not include any addition from other greenhouse gases, IPCC's 1995 scenario for stabilisation at 550 ppmv is equivalent, in terms of current modelling, to a scenario that would eventually result in a nearly constant carbon dioxide concentration of 450-500 ppmv. Both eventually produce a global mean surface temperature about 3°C above the pre-industrial level.

2.38 In this report we address the environmental impact of energy use and concentrate on carbon dioxide. Not only has it made the greatest contribution to the current enhancement of the greenhouse effect, it is by far the most important greenhouse gas in the long run because of the large, and increasing amounts being emitted, and because it is chemically stable and remains in the atmosphere for a long time. However, measures to control emissions of all greenhouse gases are also of great importance, and UNFCCC makes provision for that. Also very important are measures to limit carbon dioxide emissions that result from changes in land use rather than burning of fossil fuels, an aspect to which we return in later chapters.

2.39 Nothing the world community can now do will prevent climate change occurring on a substantially greater scale than has happened already. But measures to limit the increase in the carbon dioxide concentration in the atmosphere could bring major benefits. In addition to any benefits from reducing the concentration eventually reached, such measures could have major effects in spreading changes over longer periods. Under the 750 ppmv scenario, for example, an increase of 2°C in the present global mean surface temperature would be deferred for 50 years (from the 2050s to the 2100s), and by 100 years under the 550 ppmv scenario. A rise in sea level of 0.4 m would be deferred from the 2080s by about 25 years under the 750 ppmv scenario and by 40 years under the 550 ppmv scenario. A slowing in the rate of change would be a major benefit because it would reduce the urgency and magnitude of the adaptations human communities will have to make and increase the possibility that wildlife communities can adapt.

In the 2080s the number of people it is estimated would be affected each year by coastal flooding (2.29) would be reduced from 94 million (under IS92a) to 34 million (750 ppmv) or 19 million (550 ppmv). Although the 750 ppmv scenario brings little benefit in terms of the number of people who would be affected by water shortages in the 2080s, under the 550 ppmv scenario the number might be reduced from 3 billion to 1 billion.[40]

2.40 Greenhouse warming has the potential to cause very serious environmental damage and social upheaval. It appears to us reasonable that governments should take action to slow the rate of change and limit the concentration of carbon dioxide in the atmosphere to levels well below those that would result if past trends continue.

2.41 UNFCCC provides a mechanism for global action. In the next chapter we review the full range of possible measures to limit the concentration of carbon dioxide in the atmosphere and make an assessment of their practical potential. In chapter 4 we consider what kind of global response is appropriate to the scale and nature of the challenge, how far international action to counter climate change needs to go beyond what has already been agreed, and how such an agreement might be achieved. We consider what position the UK should adopt in international negotiations. Then, in part II of our report, we consider the implications for the UK's own policies as they affect future emissions of carbon dioxide from the burning of fossil fuels.

The concentration of carbon dioxide in the atmosphere is already higher than for possibly 3 million years. This is having a discernible effect on climate. The prospect is of much larger increases in carbon dioxide concentration, temperatures and sea level, and the impacts would be seriously damaging. Limiting the amount of carbon dioxide in the atmosphere would have a worthwhile effect in slowing down that process