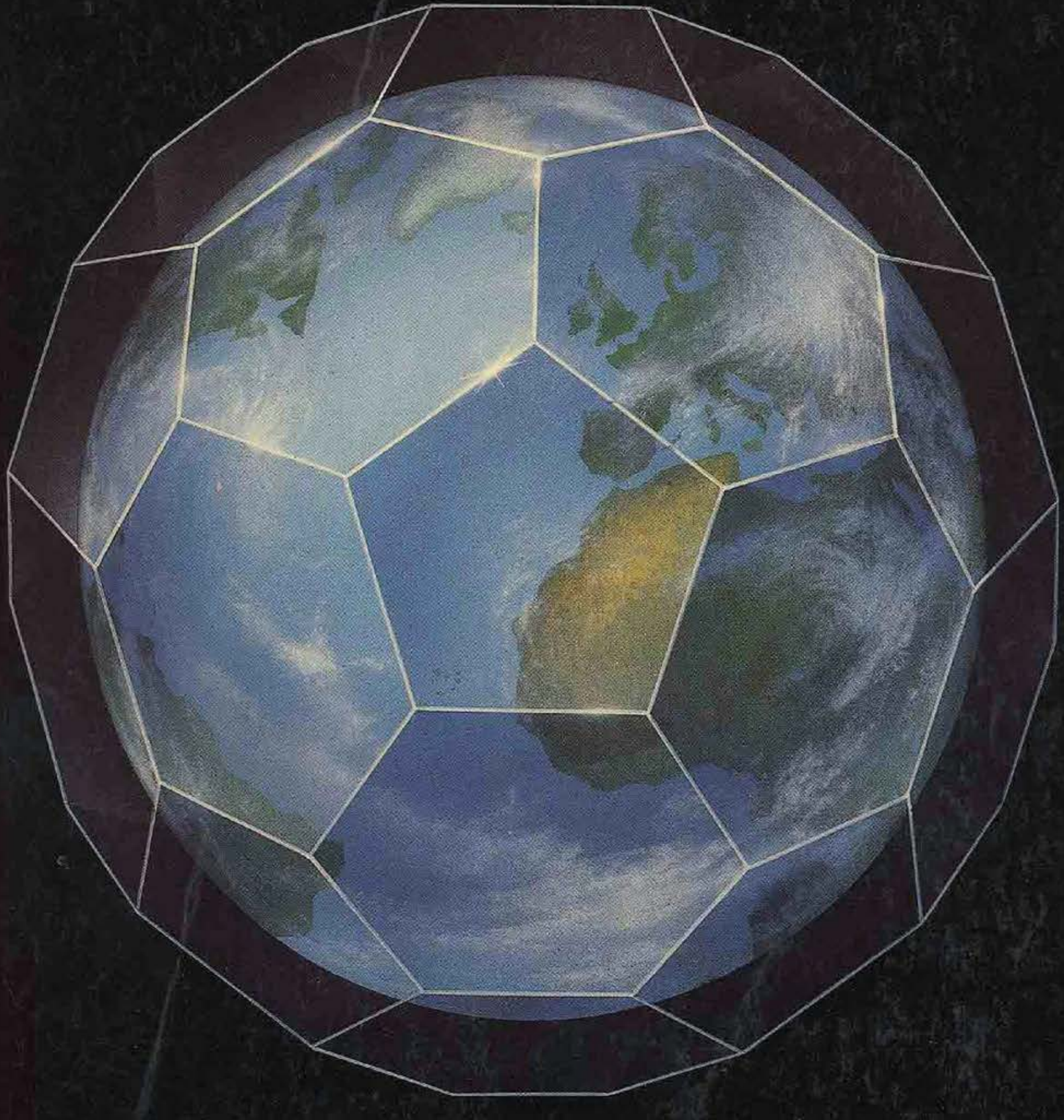
UNEP/GEMS Environment Library No 1

THE GREENHOUSE GASES



United Nations Environment Programme
The Greenhouse Gases
Nairobi, UNEP, 1987
(UNEP/GEMS Environment Library No 1)

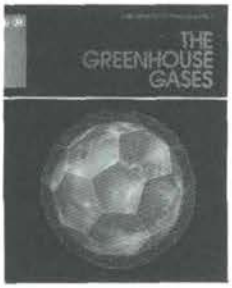
United Nations Environment Programme
PO Box 30552
Nairobi, Kenya

Text and layout: Robin Clarke
Design and artwork:
Chapman Bounford and Associates

UNEP/GEMS Environment Library No 1

THE GREENHOUSE GASES

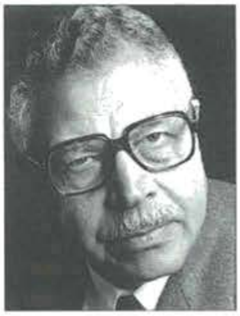
CONTENTS



Cover illustration, by Bob Chapman, depicts the Earth trapped in its greenhouse of trace gases caused by increasing pollution of the atmosphere

Foreword

Atm
311/75



Mostafa K. Tolba
Executive Director
United Nations
Environment
Programme

The Earth's climate, over the millennia of its existence, has been shaped by the cosmic forces of nature—by the cooling of the Earth's core, variations in the intensity of the Sun, changes in the tilt of our planet. These were accompanied by remarkable alterations in the life forms our planet supported. Life itself probably emerged from the 'primeval soup' of the first oceans. The hot and humid Cretaceous period led on to the the dinosaurs and pterodactyls of 100 million years ago. The last few million years have been marked by alternate Ice Ages and warm periods. Sea levels fell during the Ice Ages and rose again as ice and glaciers melted.

Today's climate is being changed by events that have taken—on a cosmic timescale—but the batting of an eyelid. In the 300 years or so that have encompassed the agricultural and industrial revolutions, man has begun to replace nature as the engine of climatic change. Today, the activities of four and a half billion human beings may be changing the climate faster than any natural event.

This is a fact of life, and there is little point in pondering its morality. There is point, however, in asking where the process is leading us. Until recently, the process was inadvertent. It is no longer so. We now know that to continue increasing the concentration of certain gases in the atmosphere will lead inevitably to a warmer, and probably wetter, planet. How warm, how wet, and how soon are three of

The UNEP/GEMS Environment Library

Since the United Nations Environment Programme was created, more than a dozen years ago, public understanding of the environmental issues confronting our planet has increased enormously. Issues such as deforestation and desertification, of which few people had even heard in the early 1970s, are now the subject of widespread public discussion.

UNEP, by disseminating information on these issues through the press, radio and television, has played a major role in environmental education. Yet many of us within the organization have become increasingly aware of a gap between what we do and what we tell the public.

This gap has arisen as the results of our environmental assessments—conducted through the Global Environment Monitoring System (GEMS)—have become more numerous and more detailed. These assessments, which cover subjects ranging from urban air pollution to climate modification, from the growing list of threatened species on our planet to the degradation of our tropical forests, are regularly published. But, until now, they have been published in forms that are understandable only by technical experts.

the questions that scientists are learning to answer. We await their definitive response with some trepidation.

The need for a greater understanding of the problem was fully appreciated by the early 1970s, when the United Nations Environment Programme (UNEP) was created. UNEP, the World Meteorological Organization and the International Council of Scientific Unions joined forces to place the study of the greenhouse effect on a firm scientific footing. At that time, it was estimated that carbon dioxide levels in the atmosphere would double by the year 2030. Then came the oil price increases of the 1970s, a cut-back in world energy consumption and a new forecast—that it would take another century to double carbon dioxide levels. Since then, we have discovered the potent potential effect of other greenhouse gases—an effect that threatens, again, to double the effective carbon dioxide level by 2030. We have come full circle, by a rather roundabout route.

This publication summarizes our current knowledge of the subject in a way that is understandable to all. I hope it will stimulate widespread public interest in the subject, and spur those who can help devise policies for the protection of the Earth's climate to greater and more informed efforts.

Mostafa K. Tolba
Executive Director
United Nations Environment
Programme

The UNEP/GEMS Environment Library, of which this is the first volume, is designed to fill that gap. Its aim is both simple and ambitious: it is to provide authoritative statements, written in plain language, about the major environmental issues with which we are faced. The volumes in this series will be attractively designed, and will provide readers with succinct summaries of the 'state of the science' in all the many topics we plan to cover. Readers will be neither patronized nor blinded with technical data.

As a result, we hope that this series will appeal to a wide audience, ranging from politicians to development experts, and from students to senior academics.

Michael D. Gwynne
Director
Global Environment Monitoring System
United Nations Environment Programme

Overview

Increasing concentrations of trace gases in the atmosphere are likely to produce a substantially warmer climate on the Earth. These gases may already be interfering with the way the Earth maintains its temperature balance. By absorbing some of the radiation emitted by the Earth in the far infrared region of the spectrum, they can force the temperature of the Earth—like that of a greenhouse—to rise. The concentration of some of these gases is increasing fast. If present trends continue, a global warming of a few degrees Centigrade will be inevitable before the middle of the next century.

a global warming of a few degrees Centigrade will be inevitable before the middle of the next century

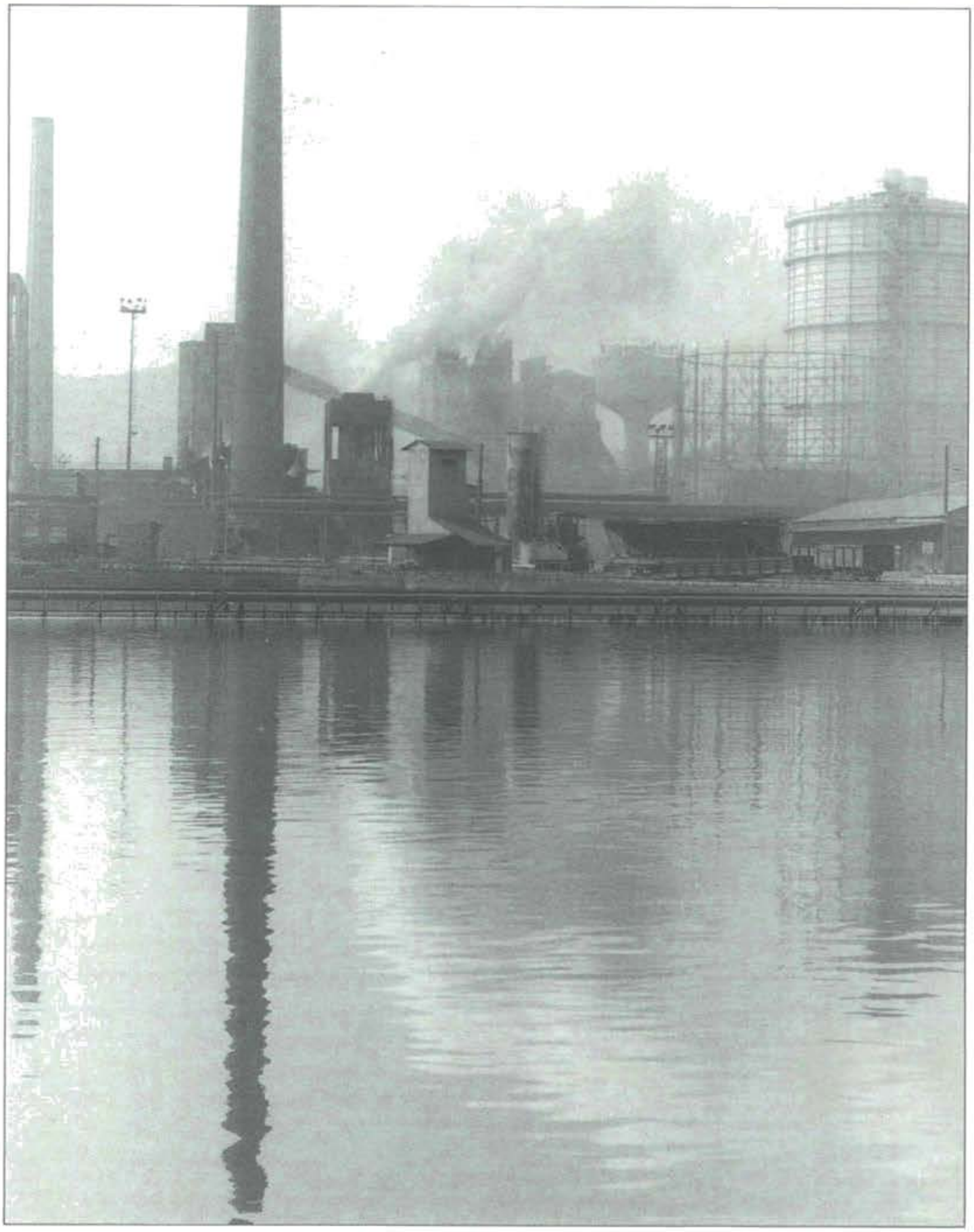
Carbon dioxide is the most abundant of the greenhouse gases, comprising about 0.03 percent of the atmosphere's volume. Its concentration has already increased by about a quarter since preindustrial times, mainly as a result of the burning of fossil fuels and clearing forest land for agriculture. Carbon dioxide concentrations are likely to increase by about a further 30 percent in the next 50 years.

Many other trace gases produce a greenhouse effect, some of them much more strongly than does carbon dioxide. The most important are methane, nitrous oxide (laughing gas), the chlorofluorocarbons (used in refrigeration, aerosol sprays and industry) and ozone which is a natural constituent of the atmosphere. Because they are present in the atmosphere in only small amounts, none will produce as large a global warming as carbon dioxide. By the year 2030, however, their combined effect is likely to equal that of carbon dioxide alone. This will approximately double the global warming that would be caused by carbon dioxide alone.

The Earth's average temperature has varied by more than 1 or 2 °C only very rarely over the past 10 000 years

The Earth's average temperature has varied by more than 1 or 2 °C only very rarely over the past 10 000 years. A global heating of even 2.5 °C would thus exceed any climatic change that occurred during the historical past. The Earth's average temperature during the most recent Ice Age, for comparison, was only about 5 °C colder than it is now.

A global warming of only a few degrees would have a profound effect on climate. Although temperatures near the equator might change little, they would increase by more than the average at high latitudes and near the poles. Higher



evaporation rates would increase annual global rainfall by an estimated 7 to 11 percent. The most extreme effects would be felt during the winter. Cold seasons would shorten and warm ones lengthen, and the annual temperature range would be reduced. In the higher northern latitudes, autumn and winter would be wetter, and spring and summer drier. Rainfall would increase in the tropics but sub-tropical regions might become drier. Increased evaporation rates would lead to drier soils over wide areas.

the burning of fossil fuels is likely to increase carbon dioxide concentrations in the atmosphere by a further 30 percent over the next 50 years

The effects that such changes would have on society are difficult to predict. Changes in agricultural production, water supply and energy demand would produce a cascade effect that might alter almost every aspect of society, including international trade, economic prosperity and individual lifestyles.

In a higher carbon dioxide world, most plants would simply get bigger

Direct climatic effects would be complicated by the fact that increased levels of carbon dioxide promote plant growth. In a higher carbon dioxide world, most plants would simply get bigger, with yields increasing by as much as a third if carbon dioxide levels doubled. Not all plants would be affected equally. Weeds might respond more to increased carbon dioxide than crops. In Africa, the staple crops of maize, millet and sorghum might be particularly vulnerable to increased competition from weeds. Soils would probably become depleted of nutrients unless more fertilizer were used. On the other hand, crops with yields that are currently limited by lack of water would fare better.

A generally warmer climate would benefit some crops in some areas but reduce production elsewhere. Many farmers would be forced to change their crops, their cultivars or their farming techniques. Where this was not possible, as in marginal food-producing areas, there might be substantial reductions in production.

Complex and unpredictable changes would also occur within natural eco-systems, as different species became dominant and others declined or died out

Outside the equatorial region, the main crop and timber growing areas would, in effect, be shifted polewards by a few degrees of latitude. Although this would probably extend the potential area of cultivation of some crops, production would fall where the shift moved crops onto poorer soils. Complex and unpredictable changes would also occur within natural ecosystems, as different species became dominant and others declined or died out.

The temperature rise is not expected to be sufficient to melt the ice cover of Greenland and the Antarctic, an eventuality that would cause substantial rises in sea level. On the contrary, increased precipitation in the Antarctic might lead to an increase in the volume of ice there, producing a small decrease in sea level. However, thermal expansion of the oceans would produce an estimated rise in sea level of between 20 and 140 cm. This might be sufficient to cause major problems for the one-third of the world population that lives within 60 km of a coastline.

Several techniques are theoretically available for reducing the scale of the greenhouse effect. The most obvious is to reduce the amount of fossil fuel burnt, either through energy conservation or by the introduction of alternative energy sources. It might also be possible to filter carbon dioxide from power station emissions, convert it to other chemical forms and dispose of it in places other than the atmosphere, such as the oceans. Methods of increasing the size of carbon sinks other than the atmosphere—which would have the effect of reducing the relative amount of carbon dioxide in the atmosphere—include major reforestation schemes and fertilizing the oceans to increase the mass of living organisms they support and hence their uptake of carbon dioxide. Finally, it should be possible to make adaptations to a changing climate to minimize its potential harmful effects.

Means must soon be found to agree on a set of priority actions and coordinate an international effort to minimize the greenhouse warming and its social effects

Intensive work is needed to establish the effectiveness, risks and costs of such schemes. Means must soon be found to agree on a set of priority actions and coordinate an international effort to minimize the greenhouse warming and its social effects.

The scientific background

Why greenhouses get hot

Most people think that plants thrive in greenhouses because of the shelter they provide from cooling winds. Most people are wrong. If that were all that greenhouses did, hot-house agriculture would never have become the growth industry that it has.

Greenhouses get hot because of the rather peculiar optical properties of glass—and, indeed, of the plastic sheeting often used instead of glass. A thin pane of high-quality glass is almost completely transparent to radiation from the Sun, letting through up to 90 percent of the radiation striking it. This radiation is then free to warm the plants, the air and the soil inside the greenhouse.

If this were all that happened, a greenhouse would simply get hotter and hotter. A cooling mechanism is also involved which stabilizes the temperature inside the greenhouse at a reasonable level—though one that is much higher than the air outside. This cooling mechanism depends on the way in which the interior of a greenhouse radiates energy back into the atmosphere and ultimately into space.

Many factors determine how much energy, and at what wavelengths, a body will radiate energy. In 1901 the German physicist Max Planck developed an equation that predicted exactly how an idealized body would radiate, given a knowledge of its temperature. Planck called this ideal body a 'black body' because his theory assumed that it was capable of absorbing all the radiation that fell on it. Although there are no real black bodies in the world, it turns out that Planck's equation predicts remarkably accurately how bodies that are far from black—including the Sun and the Earth—will radiate energy.

Everything in the universe radiates energy. The warmer it is, the more it radiates—very much so, in fact, because the rate of radiation is proportional to the fourth power of the body's absolute temperature. A greenhouse that starts the day at 15 °C or 288 K (degrees absolute), and then warms to 25 °C (298 K), will therefore increase its heat loss by a factor of $298^4/288^4$, or nearly 15 percent.

The wavelengths at which a black body radiates also depend on its temperature. Thus the Sun, which can be considered a black body at a temperature of 6000 K, radiates most of its energy in the visible region of the spectrum, at a peak wavelength of some 600 nanometres (1 nanometre is a millionth of a millimetre, or 10^{-9} m). The Earth (or for that matter a greenhouse), at 285 K, radiates most of its energy in the far infrared portion of the spectrum, with a peak at about 16 000 nm *(see Figure 1)*.

Regardless of wavelength, if the amount of incoming radiation equals the amount of outgoing radiation, temperatures will not change. So what causes greenhouse heating? The answer is greenhouse glass which, although it lets in more than 90 percent of the Sun's visible radiation, absorbs about 90 percent of radiation longer than 2000 nm. This includes much of the infrared region, and particularly the region at which bodies at 280-300 K radiate.

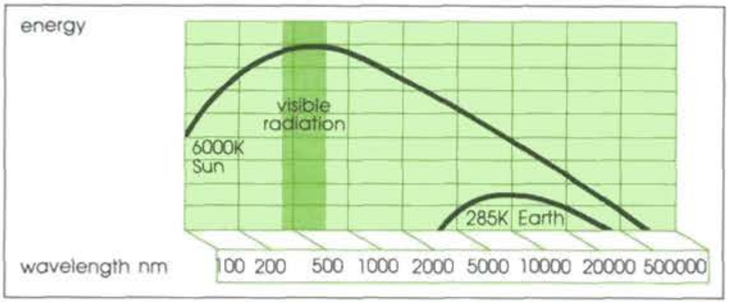


Figure 1 The Sun and the Earth behave roughly as 'black bodies' at temperatures of 6000 and 285 K (about 5730 and 15 °C respectively). As a result, they radiate at very different wavelengths

As the Sun rises, everything in a greenhouse begins to warm up because more radiation is entering it than leaving it. As the temperature rises, more radiation is emitted until—in spite of the way glass absorbs infrared radiation—the 10 percent or so that the glass allows to escape eventually compensates for the increase in incoming radiation. A new energy balance, at a higher temperature, is then created.

The Earth's heat balance

The Earth's temperature is maintained by a similar, though much more complicated, mechanism. The Earth, though not covered by glass, is covered by an atmosphere.

Imagine that 100 units of solar radiation strike the top of the atmosphere (*see Figure 2*). About 25 units are reflected back into space by the air and clouds, leaving 75 units. Some 23 units are used to heat up the atmosphere, the remaining 52 units striking the Earth's surface. Six of these are reflected back into space, the

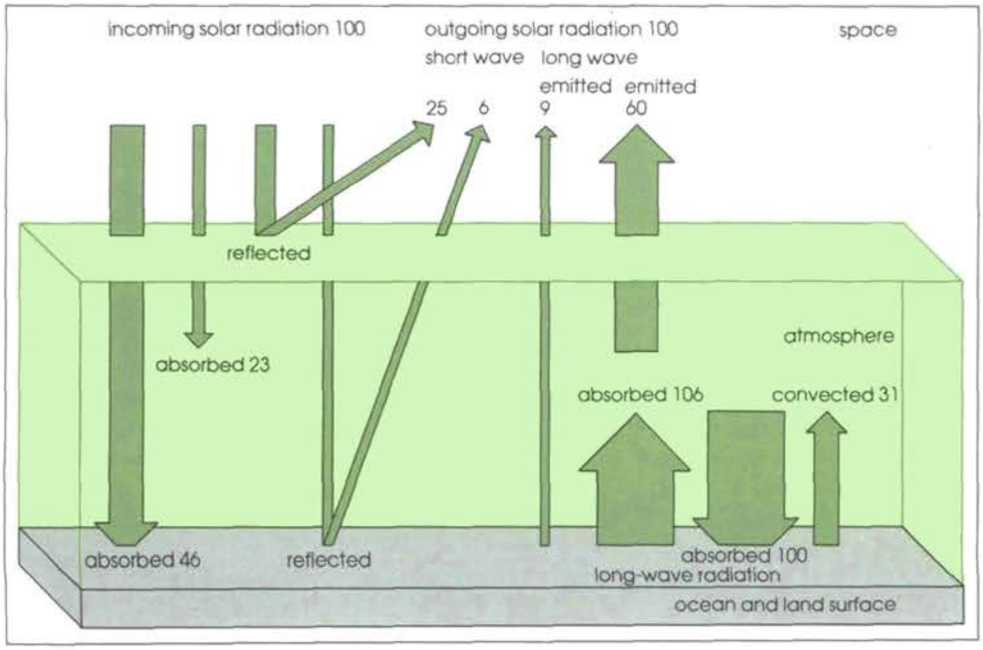


Figure 2 The Earth's heat balance is maintained through complex interactions with the atmosphere. Radiation that is absorbed at the Earth's surface is re-emitted as infrared radiation at much longer wavelengths. Most of this is then absorbed in the atmosphere which, in its turn, emits infrared radiation to space

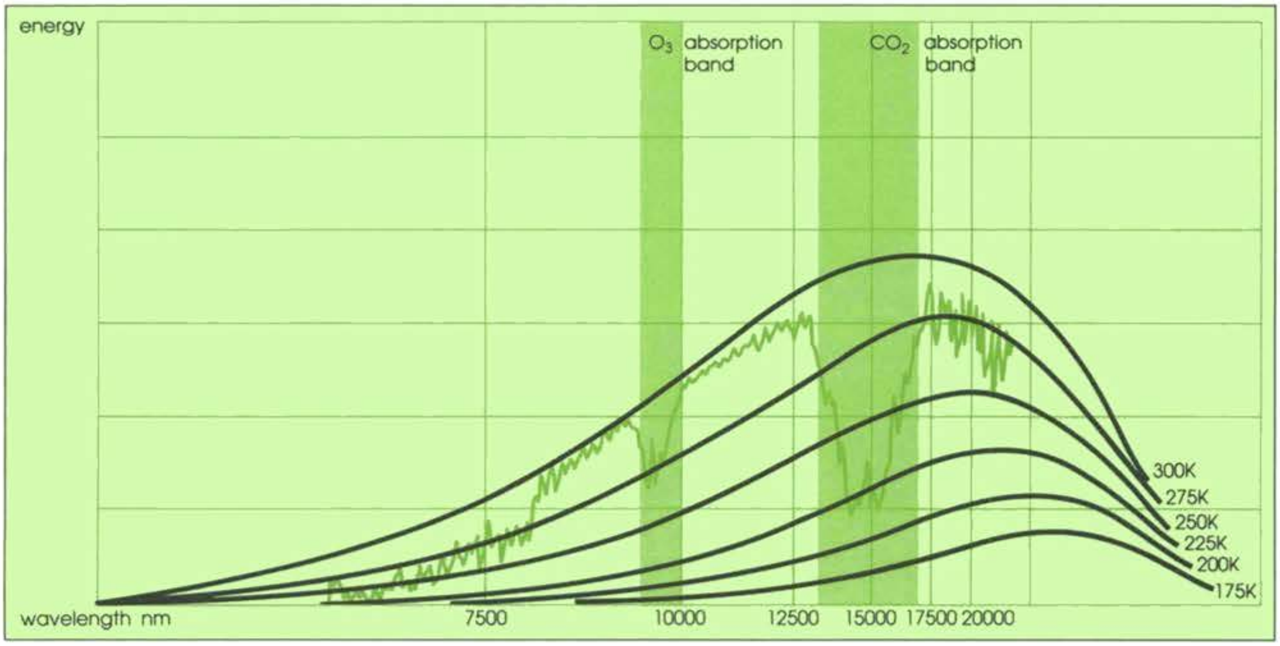


Figure 3 The radiation emitted by the Earth's atmosphere (colour) has been measured by a Nimbus satellite, and corresponds roughly to the radiation that would theoretically be emitted by a black body with a temperature of 275-300 K. The troughs in the colour curve correspond mainly to the absorption bands of carbon dioxide and ozone

remaining 46 being absorbed at the Earth's surface.

What then happens is greatly complicated by the presence of the atmosphere. Both the atmosphere and the surface warm up, and radiate infrared energy at one another. The Earth radiates 115 infrared units towards the atmosphere, of which 9 are transmitted directly into space and 106 are absorbed by the atmosphere. It also convects up to the atmosphere 31 units of energy in the form of warm air, making a total of 146 units. This appears to be more than it receives. However, it is able to do this because of infrared radiation received from the atmosphere, which radiates 100 units of infrared energy down to the Earth. Thus a net balance of 15 units of infrared radiation are emitted by the Earth's surface. These 15 units, plus the 31 convection units, make up the 46 units originally absorbed at the Earth's surface.

How does the atmosphere maintain its energy balance? It originally absorbed 23 from the Sun. To this must be added 31 convection units and the 106 of the 115 infrared units from the Earth that are absorbed by the atmosphere, making a total of 160 units. It gets rid of them by radiating 100 infrared units down to the Earth and 60 infrared units back into space. The 60 units that go back into space, when added to the 25 units reflected by the atmosphere, the 6 reflected by the Earth, and the Earth's 9 infrared units that are emitted directly into space, make up the 100 originally emitted by the Sun.

These units, of course, refer to what happens to the Earth averaged over a year. All these values change enormously between night and day, winter and summer, and the pole and the equator.

Not surprisingly, such a complicated system is potentially easily disturbed. Imagine, for example, that for some reason the polar ice caps melted. Much of the sunlight that is now reflected by ice and snow at the poles would then be absorbed by the Earth, reducing the value of the six reflected units. The Earth would then heat up, until it radiated sufficient extra infrared radiation to compensate for the extra energy absorbed.

But the potential disturbance of most importance to this publication concerns the way in which the atmosphere absorbs the infrared radiation emitted by the Earth. The complicated and dynamic interchange of infrared radiation between the surface and the atmosphere is controlled by gases in the atmosphere that absorb this radiation, just as glass does in a greenhouse.

The greenhouse effect is best explained by referring to just two of the figures used to summarize the Earth's heat balance. The Earth radiates 115 units of infrared radiation, of which 106 are absorbed by the atmosphere; the atmosphere, in its turn, radiates 60 units out into space. The difference, of 46 units, is caused by gases in the atmosphere that absorb radiation at these wavelengths. This is the greenhouse effect.

Figure 3 shows how an idealized 'black body' Earth would radiate its energy into space at various temperatures. Figure 3 also shows the radiation emitted by the atmosphere as measured from a Nimbus satellite. The two curves fit well, apart from two troughs in the observed emission at wavelengths of about 9 500 and 14 000 nm. These correspond to the wavelength bands at which ozone and carbon dioxide respectively absorb radiation. It is not difficult to imagine that were the concentrations of carbon dioxide and ozone to increase, the two troughs in Figure 3 would deepen. Less radiation would be emitted to space, and hence the atmosphere would warm up.

This picture is complicated by what would happen at the Earth's surface. As the atmosphere warmed up, it would radiate more energy towards the Earth's surface. As the Earth warmed up, it would emit more radiation but more water would also be evaporated from the Earth's surface. In fact, as the temperature increased, more and more of the extra radiation from the atmosphere would be used to evaporate water rather than heat the surface. Eventually, a new equilibrium would be established. The average temperature of the Earth's surface would certainly be higher; but the rate of evaporation from the surface would also be higher, and the atmosphere would contain more moisture. Increased cloud resulting from this increase in moisture would tend to block more incoming solar radiation, thus somewhat lessening the greenhouse effect.

The net result of increasing the greenhouse effect on the Earth is therefore not only a warmer Earth but, overall, a drier soil and a wetter atmosphere. Greenhouse heating, in other words, affects the whole of that subtle combination of temperature and moisture on the Earth's surface that we call climate.

The greenhouse gases

Though the atmosphere contains mostly oxygen and nitrogen, many other gases are also present in small amounts. The best known of these is carbon dioxide, with an atmospheric concentration of about 344 parts per million by volume (0.034 percent). But many others also contribute to the greenhouse effect. Table 1 lists the most important.

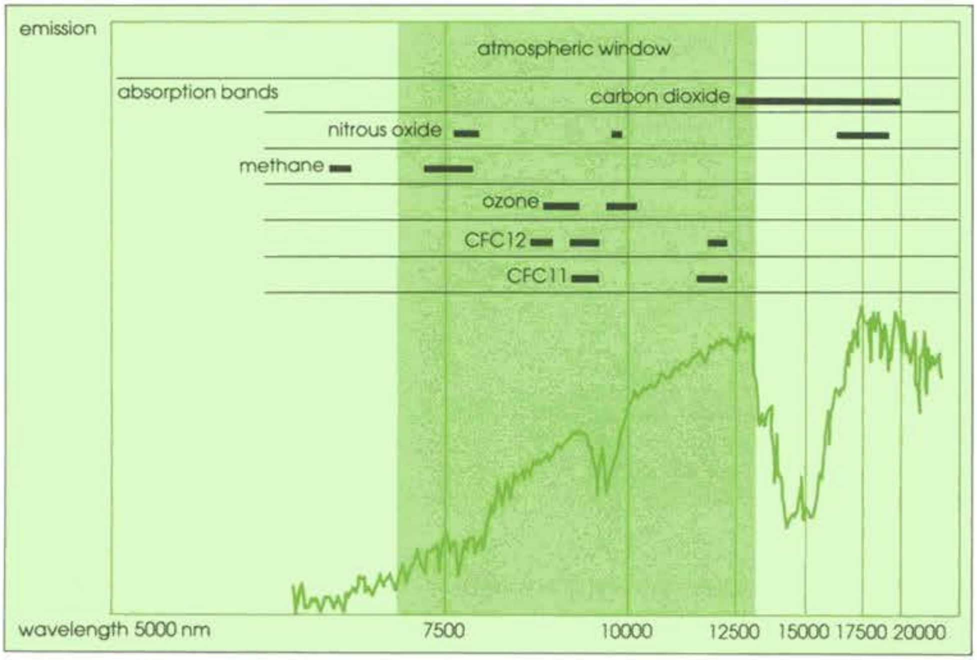
Table 1 **Greenhouse gases in the atmosphere**

	atmospheric concentration (ppbv)	annual rate of increase (%)
carbon dioxide	344,000	0.4
methane	1,650	1.0
nitrous oxide	304	0.25
methyl chloroform	0.13	7.0
ozone	variable	-
CFC 11	0.23	5.0
CFC 12	0.4	5.0
carbon tetrachloride	0.125	1.0
carbon monoxide	variable	0-2

These gases are present in very small amounts. If the atmosphere were the size of an average swimming pool, it would contain just a quarter of a drop each of methyl chloride and carbon tetrachloride, half a drop of CFC 11, one drop of CFC 12, about 30 teaspoons of nitrous oxide, some 8 litres of methane but more than a barrel of carbon dioxide. The amount of ozone would vary with depth but its maximum concentration would be the equivalent of about 5 litres per swimming pool.

Table 1 also shows the concentrations of these trace gases in the atmosphere in parts per billion, and the rates at which they are increasing. The greenhouse problem results from these increases which are ultimately caused by the fact that the Earth is becoming more populated, and its industries more numerous and, in some cases, more noxious. But, as we shall see, there are

Figure 4 Many of the absorption bands of the greenhouse gases fall within the atmospheric window—a region of the spectrum, between 7000 and 13 000 nm, in which there is little else to prevent radiation from the Earth escaping directly into space



also some unexplained factors at work.

There are also, of course, large amounts of water vapour in the atmosphere which play a major role in absorbing infrared radiation. In fact, about 90 percent of atmospheric absorption is due to water vapour, clouds and carbon dioxide in the atmosphere. The other 10 percent is due to atmospheric gases such as ozone, methane and nitrous oxide.

Figure 4 shows the way in which greenhouse gases absorb the Earth's infrared radiation. Because carbon dioxide absorbs strongly in the 12 500 to 17 000 nm band, some 70-90 percent of the infrared radiation that escapes is in the 7000 to 13 000 nm band, which is therefore known as the 'atmospheric window'. But even here, as Figure 4 shows, several trace molecules absorb some of the radiation in this region of the spectrum.

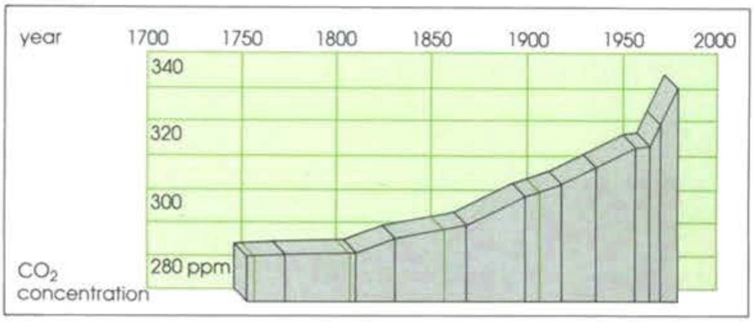
The future of the Earth's climate depends on how much the concentrations of carbon dioxide and other trace gases are likely to increase in the future. Making predictions of this kind is difficult because it requires a detailed knowledge of the sources of these gases, and of how they behave once released into the atmosphere.

Carbon dioxide: the major threat

Carbon dioxide occurs naturally in the atmosphere, and plays an important role in almost all living organisms. Animals, including humans, exhale it while plants 'breathe' it in, using the carbon it contains to manufacture the carbohydrates they need.

Before industrialization, during the first half of the 19th century, levels of carbon dioxide in the atmosphere are thought to have been about 270 parts per million by volume (ppmv). Scientists are able to determine past carbon dioxide levels by analysing the air trapped within ice in glaciers, some of which is very old and can be accurately dated. Figure 5 shows how these measurements confirm that carbon dioxide levels have been steadily

Figure 5 The analysis of air trapped in ice preserved since the 18th century shows that carbon dioxide concentrations began to rise early in the last century—and have continued to do so ever since



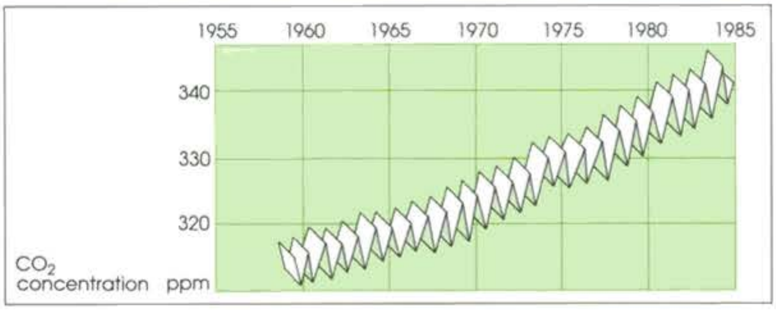


Figure 6 Accurate measurements of carbon dioxide concentrations in the air began in 1958. They show a steady rise over the years. Annual oscillations are due to a seasonal swing caused by increased vegetation in the summer. Measurements are from Mauna Loa, Hawaii

increasing since the late 19th century.

Accurate measurements of carbon dioxide levels in the atmosphere have been made only since 1957. Figure 6 shows the steadily rising carbon dioxide levels since then. Overall, carbon dioxide concentrations have increased by nearly 25 percent since industrialization. The main cause of this has undoubtedly been the burning of fossil fuels, during which the carbon the fuels contain is oxidized to carbon dioxide and released into the atmosphere. The destruction of much forest land has also contributed to the rise, because when land is cleared for agriculture the trees it once supported are usually burnt. Exactly how large an effect this has had on carbon dioxide levels is not accurately known, but it seems fairly certain that this effect will become less important in the future—partly because the rate of forest destruction is expected to slow and partly because fossil fuels are expected to be burnt in much greater quantity.

It would seem, therefore, that if guesses were made as to how much fossil fuel is likely to be burnt in the future, it would be a simple matter to predict future levels of carbon dioxide in the atmosphere. Unhappily, things are rarely that simple. What happens to carbon dioxide when it is released into the atmosphere is extremely complicated. The average carbon atom, for example, spends its life being shunted from one place to another—from a fossil fuel to the air, from the air to the oceans (in the form of dissolved carbonates), from the oceans to fish and other marine organisms, from them to the sea bed, from there to the surface again, and thence to the atmosphere whence it may be used by plants, enter the soil and eventually end up again

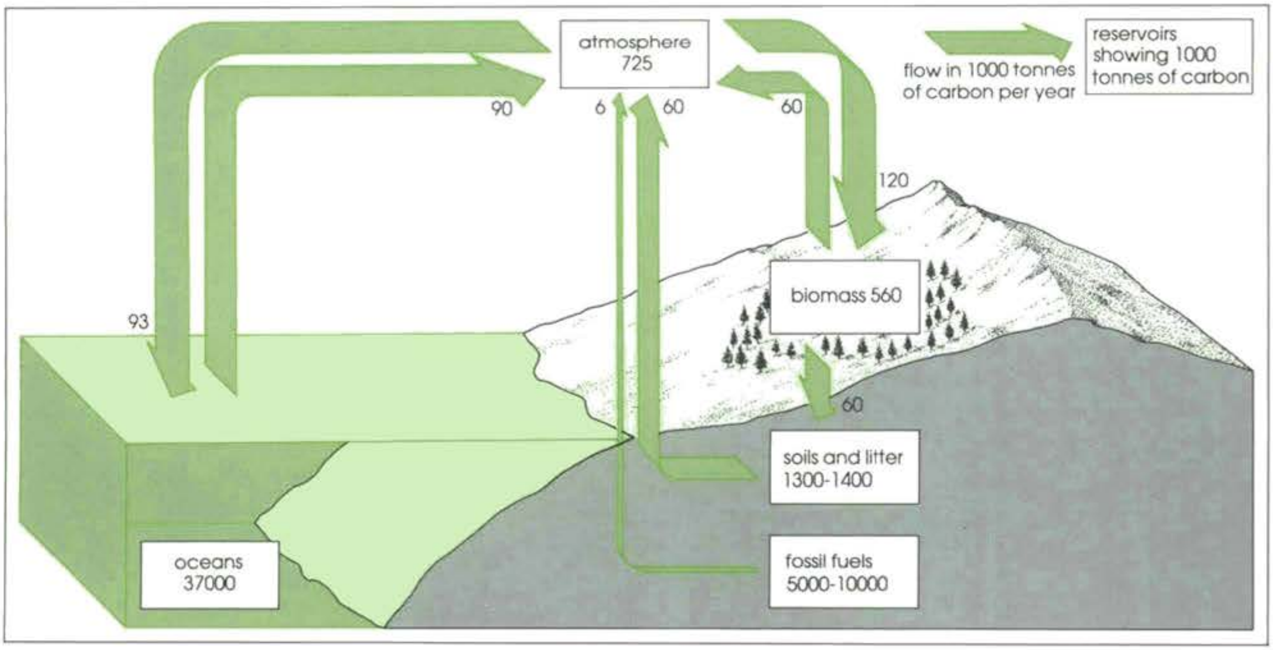


Figure 7 The global carbon cycle shunts carbon between four main sinks—the atmosphere, the oceans, the soil and the Earth's biomass. As a result, only about one half of the carbon dioxide emitted into the atmsophere stays there, the rest finding its way into the oceans, the soil and vegetation

as a fossil fuel. Even then, the cycle will start again.

Figure 7 summarizes what is known about the global carbon cycle. The effect of burning fossil fuels on atmospheric levels of carbon dioxide can be accurately assessed only if the workings of the entire carbon cycle are perfectly understood. As yet, they are not—although they are understood sufficiently to provide a useful guide as to what might happen as more fossil fuel is burnt. So far, most of the projections that have been made assume that roughly one half of the carbon dioxide released into the atmosphere stays there—the other half being absorbed by the oceans and plant life.

The first job is thus to estimate how much fossil fuel is likely to be used in the future. This is an immensely complicated undertaking. Factors that have to be taken into account include future population levels, rates of economic growth, changes in the type of fuel used, the introduction of non-fossil fuel energy technologies, the success or failure of development policies for the Third World, fuel pricing policies, and what effect warnings about global climatic changes as a result of carbon dioxide increases may have.

As Figure 8 shows, rates of emission of carbon dioxide increased steadily between 1860 and about 1910, at 4.22 percent a year, starting from about 90 million tonnes a year. Analysts of that period might have had little hesitation in predicting a continued increase at the same level until 1985. They would thus have predicted a 1985 emission level of about 16 gigatonnes of carbon a year (a gigatonne is a thousand million tonnes, or 10^9 tonnes). In fact, current emission levels are only some 5 Gt, and their predictions would have been wrong by a factor of more than three. The reasons—that could not have been predicted—include the occurrence of two world wars and the sudden rise in oil prices in 1973 and 1979.

The period 1950-1970 was another period of steady increase, at some 4.44 percent a year. But the oil price rises of the 1970s upset this steady progress, with the result that emission levels actually fell for at least three consecutive years during the early 1980s. No one yet knows what effect the sudden collapse of oil prices in 1986 will have.

Predicting future carbon dioxide emissions by the middle of the next century is, therefore, hazardous. Many people have tried to do so, and come up with widely different estimates. The lowest, made with the specific objective of

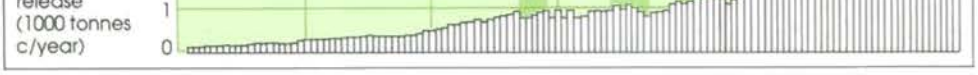


Figure 8 Fossil fuel carbon dioxide emissions have been rising steadily since 1860, though two world wars and the oil price rises of the 1970s produced minor fluctuations

exploring the effects of widespread energy conservation measures, suggests that emissions could fall to only 1 Gt by the year 2020. The highest suggests they could rise to nearly 50 Gt by the year 2050. Who is likely to be right? And what are the implications for the climate?

Some clues are given in a major paper prepared for a UNEP/WMO/ICSU conference on the greenhouse gases, held in Villach, Austria, in 1985. The authors concluded that, by the year 2050, emissions were likely to fall between a lower and an upper bound, which they put at 2 and 20 Gt respectively. But, they pointed out, even these represent extreme cases, implying that the chance of the truth lying somewhere in the middle range of about 10 Gt is high.

It is a poignant illustration of the hazards of forecasting to ask what a forecaster in 1910 would have predicted for the year 2050. Looking back at the perfectly smooth rise of 4.22 percent annually over the previous 60 years, he might well have concluded that this rise would continue uninterrupted. If so, global carbon emissions by 2050 would amount to a staggering 232 Gt! If what we think now is right, the 1910 forecaster would have been wrong by a factor of between 23 and 116.

What, then, do current forecasts of future carbon emissions imply for carbon dioxide levels in the atmosphere? One recent model of the global carbon cycle predicts that future carbon dioxide levels would reach 367 and 531 ppmv if the lower and upper bounds mentioned above were realized.

This means that carbon dioxide levels would increase by between about 1.4 and 2.0 times their pre-industrial levels by the year 2050. Many authorities are agreed that a doubling of carbon dioxide levels would produce the maximum climatic disturbance that is likely to be acceptable to future human societies. However, as we shall see, the other greenhouse gases are also likely to produce climatic change, implying that carbon dioxide levels in the atmosphere must be kept to within 1.5 to 1.7 times pre-industrial levels. If even the lower bound for energy production produces a 1.4 increase, this is a cause of great concern. Whether or not unacceptable climatic change is produced may be a close-run thing. The implications of this for future energy policy are examined later.

Nitrous oxide and methane, CFCs and others

Five other gases occur in sufficient quantity in the atmosphere, and absorb radiation in the far infra-red region strongly enough, to affect the future climate. They are: two chlorofluorocarbons (CFC 11 and 12), methane, nitrous oxide (laughing gas) , and ozone.

On a molecule for molecule basis, these gases absorb infrared radiation much more strongly than carbon dioxide. However, because they are present in the atmosphere in much smaller quantities than carbon dioxide, their effect is much smaller. As we shall see, their combined effect is likely to be roughly equal to that of carbon dioxide itself.

The problems of predicting the future levels of these greenhouse gases in the atmosphere are even more severe than that of predicting future carbon dioxide levels. One reason is that the cause of the increasing concentrations of some of these gases is very inadequately understood.

Methane concentrations were not measured until the late 1960s, and measurements made during this decade show a strong upward trend (*see Figure 9)* of about 1.1 percent annually over the past 10 years. Ice cores containing trapped air have been used to analyse longer-term trends, and show that methane levels have been rising more or less in parallel with the growth of the human population (*see Figure 10*).

This makes sense because methane is produced in a number of agricultural activities—for example, in the stomachs of ruminating cattle and at the bottoms of rice fields—as it is during coal mining and when fossil fuel is burnt. However, no one is certain how much methane is produced

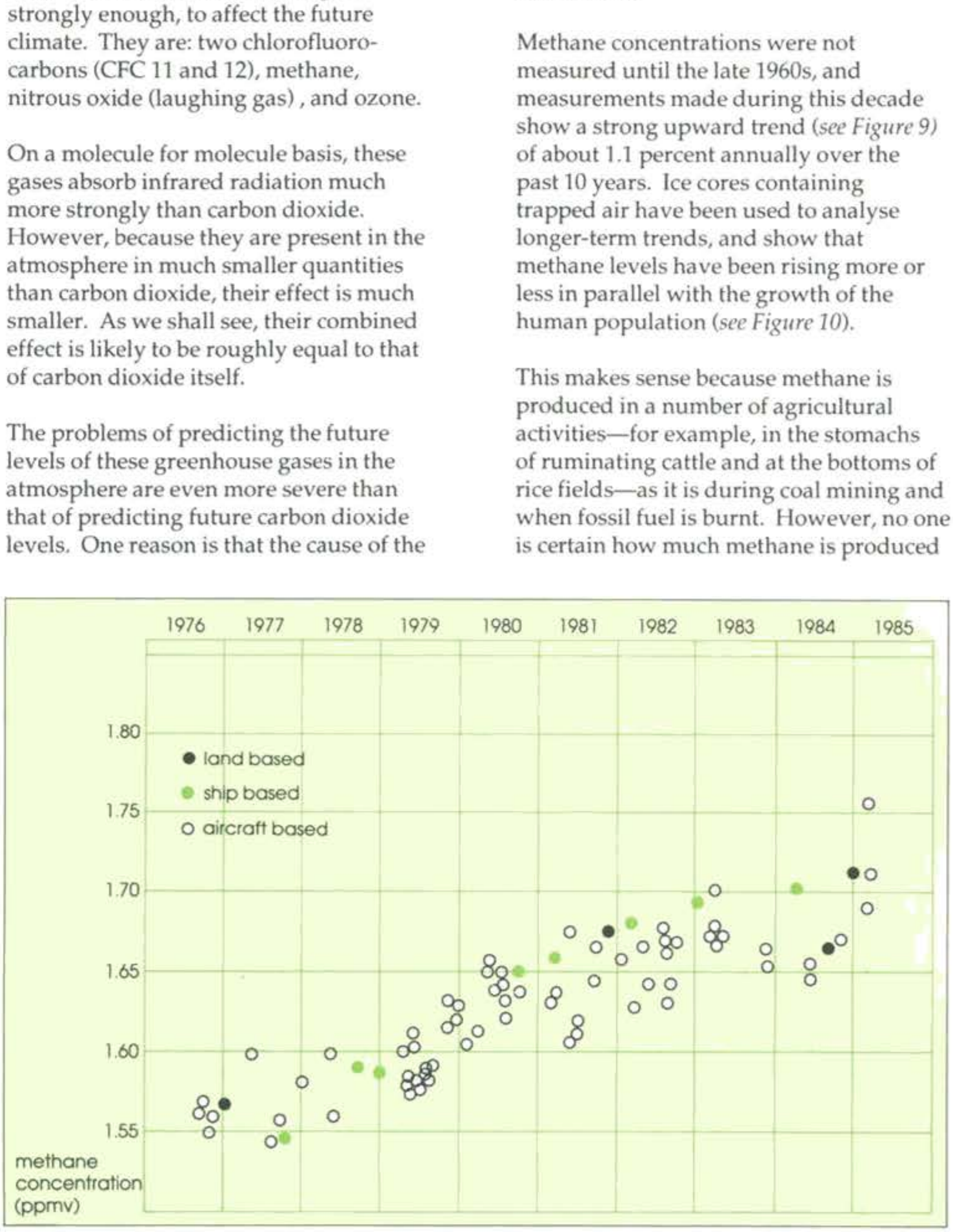


Figure 9 Methane levels in the atmosphere have been increasing at a rate of about 1.1 percent annually over the past decade. Measurements have been made from aircraft , from ships and on land

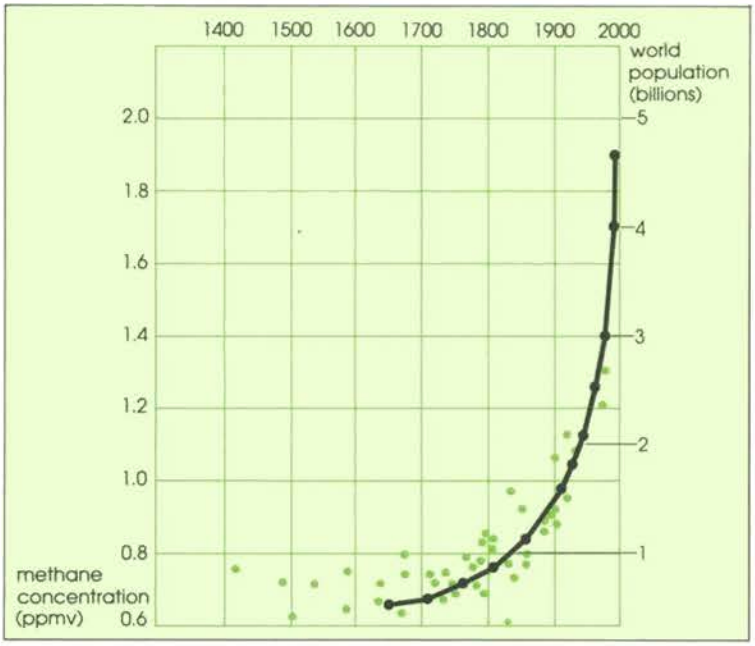


Figure 10 Growth of the human population (black) and levels of methane in the atmosphere (colour) have followed one another closely over the past 600 years. Most predictions about future levels of methane in the atmosphere assume that this correlation with population growth will continue to hold

by each activity. Rumination, rice farming and fossil fuel burning appear to contribute the most, in roughly equal amounts, and swamps, the exploitation of natural gas and coal mining make up most of the rest.

Every year an average of about 425 million tonnes of methane are released into the atmosphere. However, methane does not have a long lifetime in the atmosphere (the average molecule stays there only about 10 years) because it is fairly rapidly oxidized to other chemicals. Oxidation, and the other processes that destroy methane, account for about 375 million tonnes a year, leaving an annual excess of some 50 million tonnes. This is the amount by which methane levels are now rising annually.

How much are future methane levels likely to rise? So far, methane concentrations have roughly doubled from pre-industrial levels of about 0.7 to about 1.65 ppmv. One way of estimating future levels is to assume that the relationship between methane levels and human population illustrated in Figure 10 continues to hold. If it does, methane levels would reach about 2.5 ppmv by the year 2050. A figure of about 2.34 ppmv by the year 2030 (an increase of some 40 percent over today's value) seems reasonable. But much will depend on what happens to the levels of the other chemicals in the atmosphere that control the rate at which methane is oxidized.

Like methane, nitrous oxide or laughing gas is also produced both naturally and artificially, and its concentration is increasing—though much more slowly, at about 0.2 to 0.3 percent a year. The current concentration is about 0.3 ppmv, equivalent to some 1.5 million tonnes.

Nitrous oxide is removed from the atmosphere much more slowly than methane, and has an average lifetime there of as much as 170 years. It is produced as a result of microbial action in the soil. Its rate of release is, of course, accelerated if mineral fertilizers containing nitrogen are used in agriculture. Of all the nitrous oxide released—some 12 to 15 million tonnes a year—probably about 10 percent is due to the use of fertilizer. Natural microbial activity, the spread of agriculture, and the burning of timber, crop residues and fossil fuels, account for most of the rest.

Future predictions are complicated by a number of facts. For one thing, the rate of emission of nitrous oxide seems to have accelerated sharply over the past decade or so. However, it would be unwise to assume that this increase can continue indefinitely because both fossil fuels and

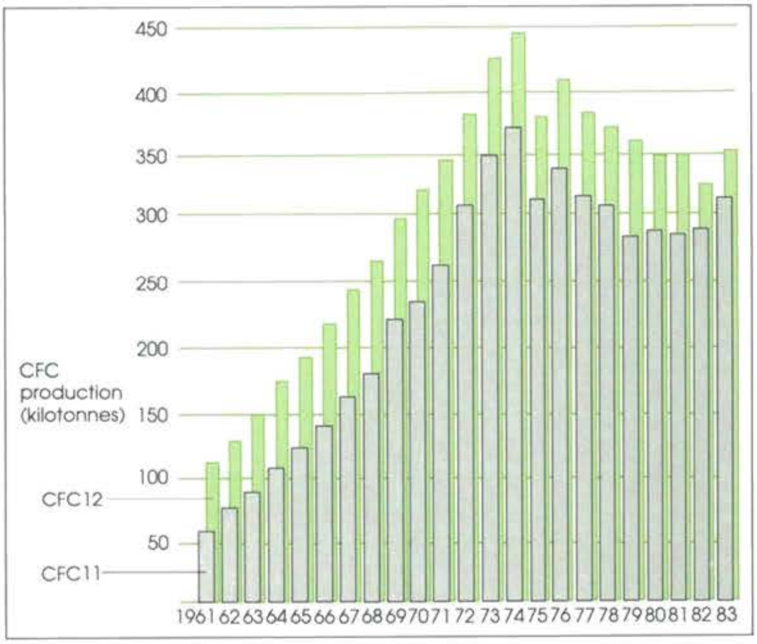


Figure 11 Production rates of chlorofluorocarbons in companies reporting to the Chemical Manufacturers' Association rose sharply until the mid-1970s when the use of CFCs in aerosols began to decline. The recent rise is due to increased usage in other applications

the area of potentially cultivable land are limited. Moreover, because nitrous oxide has such a long residence time in the atmosphere, a steady state condition—in which nitrous oxide levels in the atmosphere stop rising—may not be reached for a further 200 years, even if emission stopped rising now. The consensus is that, bearing these facts in mind, likely nitrous oxide levels in the year 2030 will be around 0.375 ppmv—an increase of some 34 percent over pre-industrial levels.

The CFCs or chlorofluorocarbons are used as the working fluids in refrigeration, as propellants in aerosols, as solvents and as foam-blowing agents in the production of plastics. Unlike the other greenhouse gases, they are not produced naturally and their presence in the atmosphere is due solely to industrial production. Virtually all CFC production eventually ends up in the atmosphere.

Because the CFCs release free chlorine in the upper atmosphere, which then catalyses the breakdown of ozone, they are a threat to the ozone layer which protects life on Earth from the harmful effects of solar ultraviolet radiation. For this reason, a number of nations have introduced restrictions on the production of CFCs or the uses to which they are put. An international Convention for the Protection of the Ozone Level has also been drawn up, and may soon be followed by a protocol requiring signatories to it to regulate the production or use of CFCs.

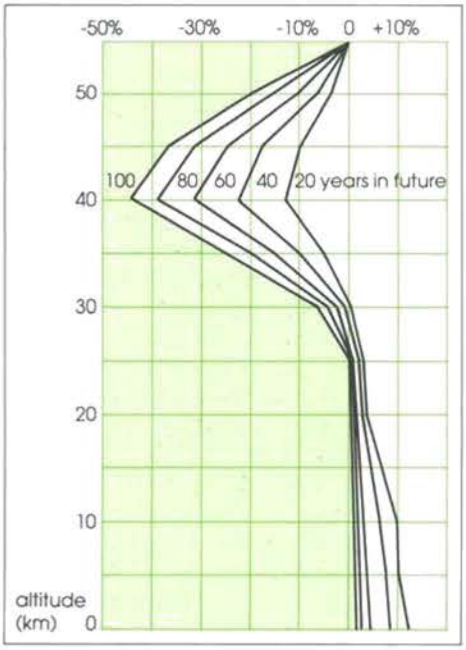
Although CFC production increased sharply until about 1970, emission rates then slowed down as the new restrictions began to take effect. However, there are signs that CFC production is again increasing (*see Figure 11*). CFCs have a long atmospheric lifetime, and it is therefore important that action is taken quickly to halt or slow down the increasing concentration of CFCs in the atmosphere. For this reason, current trends are probably a poor indication of what may happen in the future. Most forecasters make either an optimistic prediction that CFC production will increase annually by some 1.5 percent or, pessimistically, that it will increase at 3.0 percent (compared to a 1980 level of 5 percent annually).

The problems that ozone presents are very different. Ozone is a natural constituent of the atmosphere, and life on Earth depends on its presence. Ozone concentrations vary widely with height, latitude, season and time of day—which makes the long-term detection of changing ozone concentrations very difficult. However, ozone concentrations appear to be increasing in the lower atmosphere. This is caused by increases in the concentration of other molecules, such as carbon monoxide, that catalyse the reaction in which ozone is formed from oxygen. This finding is important because it is in the lower atmosphere that ozone could play its principal role as a greenhouse gas.

Higher up, say above 25 km, there is some evidence that ozone levels are beginning to show a small decline—as would be expected as CFC levels rise, release free chlorine, and hence speed the breakdown of ozone. At these heights, ozone plays a quite different role in altering climate. The ozone molecule absorbs solar radiation. Hence if ozone levels were to fall high up in the atmosphere, less solar radiation would be absorbed there, and more would be available to travel down through the atmosphere and strike the Earth's surface. On the other hand, the atmosphere itself would absorb less solar radiation and therefore radiate less infrared radiation at the Earth. Whether these two opposing effects would balance one another out, or whether one would predominate, has yet to be satisfactorily resolved.

The problem of predicting future ozone levels is that they depend almost entirely on the future concentrations of other chemicals—and even these must be considered interactively because the chemistry of what happens in the upper atmosphere is so complex. Most scientists believe that ozone levels up to a height of about 9 km will continue to increase, perhaps by about 0.25 percent a year. Higher up, this effect will become smaller, reducing to zero at 27 km. Above that, there will be substantial ozone level decreases caused by increasing concentrations of the CFCs and other gases. One prediction of future ozone levels is shown in Figure 12.

Figure 12 Atmospheric model predictions of ozone levels at various heights in the atmosphere over the next 100 years. Though ozone will be depleted above 25 km, its concentration will increase at the lower levels at which it produces its greenhouse effect



How will climate change?

Given a knowledge of how concentrations of the greenhouse gases are likely to change over time, it is relatively simple to predict the resulting changes in solar and infrared radiation at the Earth's surface. Translating those changes into a realistic prediction of future climates is, however, far more difficult.

What is needed is a computer model of the Earth's climatic system that will predict the climatic changes that result from changes in the levels of incoming solar and infrared radiation. Furthermore, this model must allow for feedback mechanisms. For example, if the Earth's surface warms up, more snow and ice will melt, less solar radiation will be reflected from the Earth's surface, and temperatures will tend to increase even more. Similarly, climatic change will affect cloud cover and the amount of water vapour in the atmosphere, and these changes will affect climate further. As an example of how important these effects are, nearly all models without feedback predict a temperature rise of 1.2 to 1.3 °C if carbon dioxide levels are doubled. Introducing feedback produces results that agree much less closely and which lie mainly within the range 1.5 to 4.5 °C.

Though such figures sound small, they represent average annual increases. For comparison, the average temperature during the most recent Ice Age was probably about 5 °C colder than it is now. Studies of past climates have been successfully used to show how wide a climatic change can be produced by just a small change in average annual temperature. For example, there was a period some 5000 to 7000 years ago when the average temperature was perhaps 1 °C warmer than it is now. The climate then was substantially different from today's. There was more rainfall in the tropics and sub-tropics (probably 50 to 100 percent more in Africa and India), and the Sahara was probably not a desert but dry savanna.

It is fairly certain that the average temperature has not varied by more than 1 or 2 °C during the past 10 000 years. This means that if a doubling of carbon dioxide raises temperatures by even the lowest estimate of 1.5 °C, the climate that results will be beyond the range of any climate that has existed during recent history.

The models of the atmosphere that are currently available are far from perfect. For example, most treat the oceans as a kind of swamp in which there are no horizontal movements. All have trouble incorporating feedback mechanisms due to clouds, the warming of the oceans and changes in sea ice cover. And, because these models are still only crude approximations of what happens on the Earth, they cannot yet reliably predict regional differences in climate—although they do provide an indication of what might be expected.

Most of the models analyse what would happen if carbon dioxide levels were to double—that is, if they were to rise from their current levels of 344 ppmv to about 680 ppmv, reaching about 450 ppmv in 50 years time, by the year 2030. However, the effect of other greenhouse gases must also be considered. These can be easily computed—given predictions of their future concentrations—and Figure 13 shows the relative roles of carbon dioxide and the other greenhouse gases in 50 years time. In broad terms, the other gases are expected to have a roughly equal effect to that of carbon dioxide alone. Whatever effect carbon dioxide is likely to produce on its own by then is thus

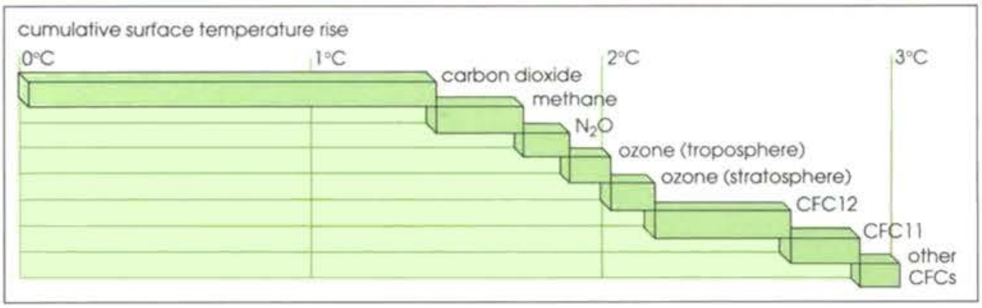


Figure 13 A global warming of about 3 °C is predicted for the year 2030. Half the rise will be attributable to the increased concentration of carbon dioxide, the other half to increases in the concentrations of other greenhouse gases

likely to be approximately doubled.

One way of expressing the part the other gases would play is to calculate their 'carbon dioxide heating effect'. In 1980, the other greenhouse gases present in the atmosphere would have produced a greenhouse heating equivalent to an extra 40 ppmv of carbon dioxide; by 2030, their effect would be the same as an extra 140 ppmv of carbon dioxide. This provides new values for effective carbon dioxide levels. The pre-industrial level would remain unaltered at 270 ppmv; 1980 levels would rise to 380 ppmv; and 2030 levels would reach 590 ppmv. Thus if all the greenhouse gases are considered, the rise in effective carbon dioxide levels from pre-industrial times to 2030 would be 2.2 times. The rise between 1960 and 2030 would be more than 1.8 times, in effect a doubling.

Most experiments with atmospheric models have concentrated on the effects produced by a doubling of carbon dioxide concentrations. As far as the climate is concerned, it is irrelevant whether these changes are produced by a doubling of carbon dioxide itself, or an equivalent temperature rise produced by all the greenhouse gases. The results quoted below can thus be considered as an indication of what is likely to happen between about 1960 and 2030 as a result of increased concentrations of both carbon dioxide and the other greenhouse gases.

On this basis, most of these models suggest that the Earth's average surface temperature would increase by some 4 °C—in fact, the range of results from the three most recent models is between 3.5 and 4.2 °C. The warming would be most marked in the Northern hemisphere in the winter at high latitudes. In the Southern hemisphere, the largest warming would occur in Antarctica. One model (*see Figure 14*) suggests that the average air temperature would increase by about 4 °C over much of Europe and North America, by about 5 °C over much of the Sahara, and by even more at latitudes above 60°.

It is somewhat harder to describe the other changes predicted by these models, for they are not all in agreement. Generally, however, the models predict a retreat of sea ice, a decrease in the Earth's reflectance, and a general decrease in cloudiness. Some models, however, suggest that there will be more low-level clouds at high latitudes and more high clouds in middle latitudes.

The models also make predictions about precipitation and soil moisture. Three of the most recent model predictions suggest that overall precipitation will increase by between 7 and 11 percent, with the largest changes occurring between 30 °N and 30 °S. There is likely to be more rain in the equatorial region throughout the year, and less rain in adjacent latitudes for at least some of the year. Soils seem likely to get drier during the summer at middle and high latitudes in the Northern hemisphere.

These changes would not occur at the precise time at which carbon dioxide levels doubled for exactly the same reason that an electric kettle does not boil the moment it is switched on. The Earth—and particularly its oceans—would take time to warm up. In fact, the thermal lag of the oceans is so large that probably only about half the predicted temperature increase would occur by 2030, the other half taking a few decades longer to manifest itself.

Although many uncertainties remain, recent studies of the effects of the greenhouse gases are unanimous that there will be a warming by the year 2030. The effect could be anything from 1 to 7 °C, with a most likely value of 1.5 to 4.5 °C. Some of this warming will be delayed by thermal lag, and some of it—perhaps about 0.5 °C—has probably already occurred. Records of temperatures in the Northern hemisphere indicate that the average temperature has risen by about 0.5 °C over the past 120 years or so.

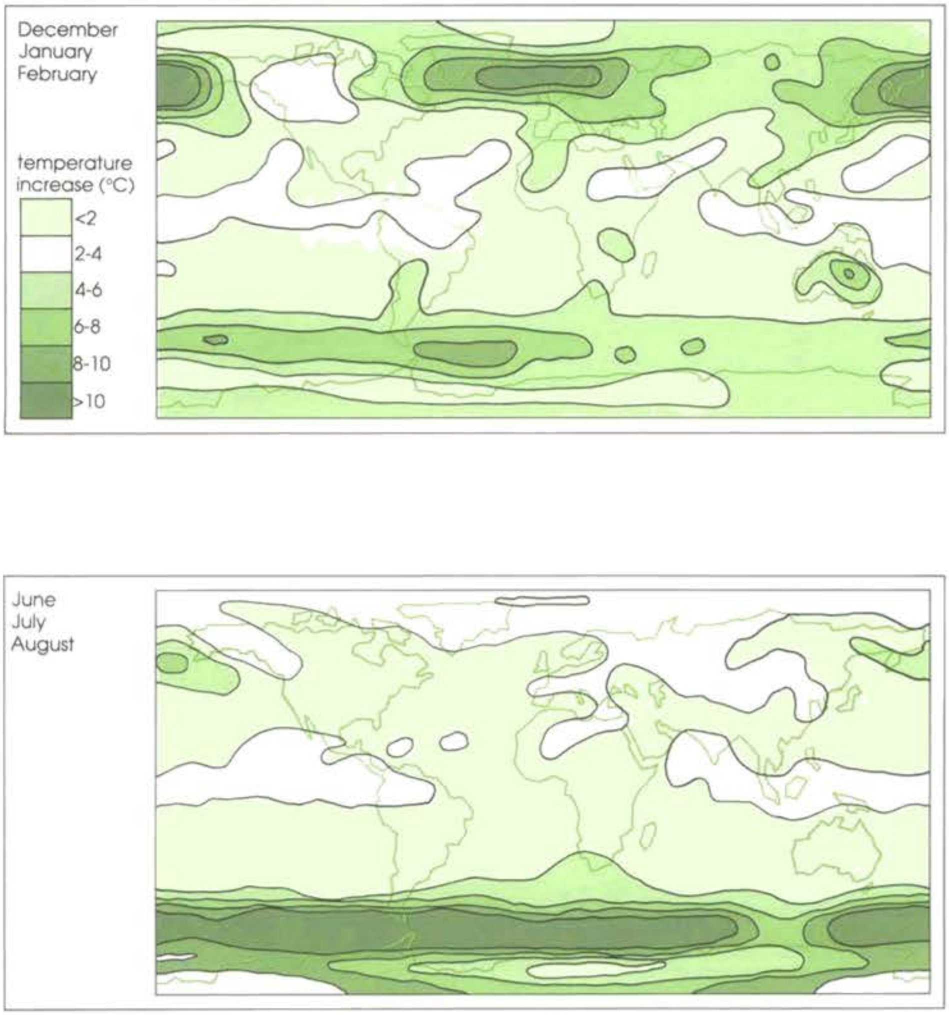


Figure 14 Atmospheric model shows the effects of a global warming in December-February (top) and June-August (bottom) as a result of a doubling of carbon dioxide concentration in the atmosphere. The effects are most pronounced in the northern winter, with temperatures rising by as much as 10 °C above the normal winter average in Scandinavia

Effects on society

When climate changes, society suffers. Essentially, this is because society is as best adapted to existing climates—with their inherent variability—as it can be. As much is evident, for example, in the way both cold, wet spells and warm, dry ones lower crop yields. The crops that have been chosen for production, and the techniques used to produce them, have already been selected for best results under average climatic conditions. If the climate changes, different cultivars, different techniques and even different crops may have to be used.

Of course, there are exceptions. Greater rainfall in the Sahel during the 1970s and early 1980s would have improved conditions there immeasurably. But these exceptions tend to occur where areas are undergoing exceptional deviations from the norm. Elsewhere, climate changes are nearly always costly, requiring new adaptations, new technologies and forcing changes in lifestyle.

It is thus misleading to talk about climatic change as though some changes will be invariably beneficial and others invariably harmful. One of the suggested 'beneficial' changes is that increased concentrations of carbon dioxide will increase plant production. This has nothing to do with climatic change. Experiments have shown that plants raised in an atmosphere enriched in carbon dioxide grow bigger than normal. By the year 2030, therefore, many crop yields are likely to increase, providing changes in temperature and rainfall do not produce large adverse affects. While increased yields might be beneficial in many areas, it is naive to imagine that they would be universally so. For example, in the United States, Japan and the European Economic Community, at least, the major agricultural problem is currently over-production. If increased yields were brought about artificially, the immediate effect would probably be to depress market prices further, increase surpluses, lower farming incomes and increase unemployment.

Even simple and minor changes in agricultural yield are therefore likely to produce a cascade of effects throughout societies, making it difficult to predict their social impact. In fact, of course, a changing climate will affect much more than agricultural yield. There are likely to be far-reaching effects on all bio-productive systems—including forests, croplands, rangelands and fisheries—as well as on the demand and supply of both water and energy. Climatic change could well exacerbate existing problems such as drought, desertification and soil erosion. It could alter the frequency of ecological hazards such as floods, storms, forest fires, and the outbreaks of pests and diseases. The occurrence of warmer, wetter winters in temperate areas, for example, might well enable harmful pests to survive winters in far greater numbers than is currently the case.

Some cities would undergo quite profound temperature changes. The temperature in Washington DC, for example, currently exceeds 38 °C on an average of only one day a year; it exceeds 32 °C about 35 days every year. But, by the middle of the next century, these figures could rise to 12 and 85 days a year. The effects of such temperature rises on human health, in Washington and similar cities throughout the world, are difficult to predict; unquestionably, urban heat stress would claim many lives.

As the atmosphere heated up, its capacity to hold water vapour would increase. This would affect rainfall, surface moisture and

increased flooding, as here in Java in 1982, could be one of the greatest dangers of a changing climate for low-lying developing countries

the prevailing hydrological balance. Apart from annual effects on crop yields, such changes might alter the viability of present-day planning. Water supply—and electricity supply in the form of hydropower—depends on structures such as dams and reservoirs that normally have an expected useful life of at least 40 years. Their design is based on the assumption that precipitation and evaporation rates remain unchanged throughout that period. If that assumption proves incorrect as a result of climatic change, planning would become an even more difficult process than it already is.

The speed at which climatic change occurs is also important. A fast change will be much harder to adapt to than a slow one, and could overwhelm society's somewhat measured response to enforced change. Climatic changes caused by an effective doubling of carbon dioxide concentrations might be easy to deal with over 100 years, possible to adjust to over 50 years but could create major problems if they occurred over 15-20 years. Nor will such changes spread uniformly over the globe. As already mentioned, the Earth's climatic system is such that while some areas may be little affected, others—including the most productive grain-producing areas in the world—may undergo major changes in temperature, rainfall and surface moisture.

Predicting the social consequences of increased carbon dioxide concentrations is made even more difficult because two effects are involved: the increase in plant growth caused by higher levels of carbon dioxide, and the effects of climatic change itself.

Plants will get bigger

Carbon dioxide is essentially a fertilizer: its presence encourages plants to increase their carbohydrate levels. Although successful farmers never apply fertilizer indiscriminately, industrialized nations—by burning increasing amounts of fossil fuel—are in effect forcing all farmers to fertilize their crops indiscriminately. If carbon dioxide levels double, it is likely that the yields of many crops—and the growth of the weeds that threaten them—will increase by about one-third.

Plants grown in laboratories under high levels of carbon dioxide—up to about 1000 ppmv for most plants—thrive. Their yields are increased and, because their transpiration rates are reduced, they use water more efficiently for plant growth. This has a marked effect on plants whose growth is normally limited by lack of water. Faster growth, of course, is not restricted to useful plants: weeds may increase their growth by as much as, or even more, than domestic species. Nor is it easy to predict the effects of increased carbon dioxide because plants vary widely in their response to it: some may more than double their growth rates while others remain virtually unaffected.

The effect depends partly on the nature of the photosynthetic pathways plants employ. In the process of converting carbon dioxide to carbohydrates, plants produce many intermediary compounds. In some species, the C_3 plants, these intermediaries contain three carbon atoms; others, the C_4 plants, produce intermediaries with four carbon atoms. The C_3 plants respond much more markedly to increased carbon dioxide than do the C_4 plants. A doubling of carbon dioxide concentrations is likely to increase the growth and yield of C_3 plants by 10 to 50 percent but those of C_4 plants by much less - only about 0 to 10 percent.

This may prove important because, of the world's 20 major food crops, 16 are C_3 plants (*see Figure 15*). On the other hand, 14 of the world's 18 most noxious weeds are C_4 plants which would be expected not to respond to carbon dioxide as vigorously as the 16 food crops. The latter might therefore be better protected from weeds than they are now. On the other hand, the four C_4 food crops—maize, sorghum, sugarcane and millet—would have to withstand increased competition from C_3 weeds. This is not a happy outlook for much of sub-Saharan Africa where maize, millet and sorghum are the staple foods. These crops would not benefit as much from the fertilizing effect of carbon dioxide as would rice and the staple crops of the temperate regions. They might also be subjected to more intensive competition from C_3 weeds.

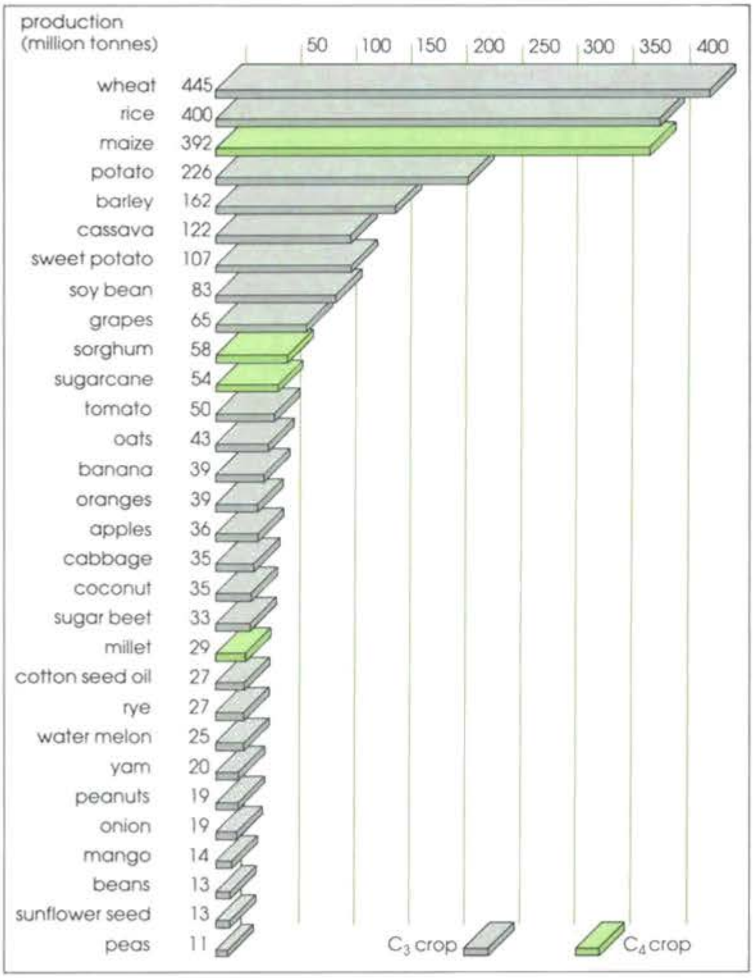
All this is complicated by the fact that the influence of carbon dioxide also depends on the plant's ability to use the extra carbon dioxide present. There is some evidence that weeds are generally more responsive to increased carbon dioxide than are crops—regardless of the photosynthetic pathways they use.

More research is needed before anyone can say exactly how much yield will be increased by a given increase in carbon dioxide. As a rule of thumb, growth seems to be increased by 0.5 to 2.0 percent for each 10 ppmv rise in carbon dioxide. This implies that, since preindustrial times when carbon dioxide levels were about 75 ppmv lower than now, plant growth should have increased by an average of 3.75 to 15 percent. Indeed, it is quite possible that the spectacular recent growth in plant yields is partly due to increased levels of carbon dioxide in the air. It is estimated, for example, that 15 percent of the soybean yield increase that has occurred since about 1700 has been caused by an increase in atmospheric carbon dioxide levels.

By 1982, nearly 800 laboratory experiments with food crops had demonstrated the carbon dioxide effect. They showed, for example, that doubling carbon dioxide concentrations would increase predicted marketable yield by widely varying amounts (*see Figure 16*).

However, the food quality of plants tends to deteriorate as carbon dioxide levels increase. Leaves become relatively richer in carbon and poorer in nitrogen. It has been shown that pests feeding off soybean leaves have to consume more to gain their required nitrogen protein levels. This suggests that agricultural pests might be more damaging in a carbon-rich environment.

Farmers would have to contend with another effect of increased carbon dioxide. If plants grew more quickly, they would need more fertilizer—unless they were leguminous, and fixed their own nitrogen, in which case they would be likely to contribute more nitrogen to the soil. Inter-cropping with legumes might become more beneficial in an increased carbon dioxide environment. The use of synthetic fertilizer might become more costly yet more essential if soils were not to be depleted of their nutrients.



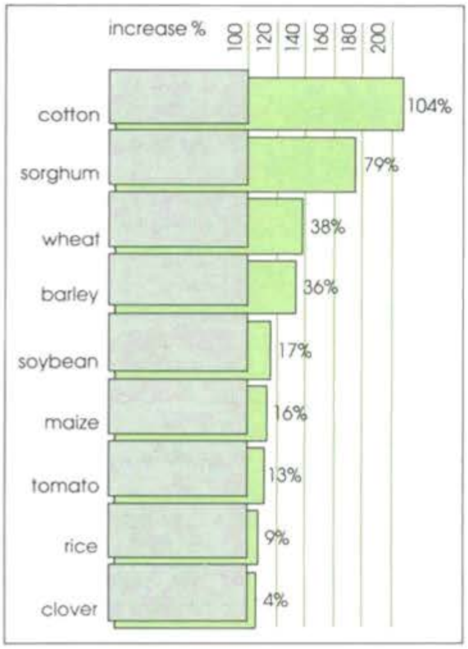


Figure 15 Of the world's 30 major food crops (top), only four are C$_4$ plants; three of these are the staple foods of most sub-Saharan African countries. Yields of the other crops are likely to increase sharply as a result of higher levels of carbon dioxide in the atmosphere

Figure 16 Predicted increase in yields (left) in nine major crops that would be caused by a doubling of carbon dioxide concentration

Effects of climatic change

Changes in temperature and rainfall would also affect agricultural yields, though in ways that are not always easy to predict. Though warmer, wetter conditions might be thought generally beneficial, this is not necessarily so. Agricultural yields are often depressed because soils become so waterlogged that harvesting is made very difficult or because muggy conditions provide an ideal breeding environment for pests and diseases.

A generally warmer environment would also alter the areas suitable for growing crops, tending to push these areas polewards. In the Northern hemisphere, for example, wheat (and, for that matter, forests) would probably grow further north than they do now. While this might be beneficial for farmers, it would depend on the nature of the soil in the new crop-growing areas. If climatic change moved crop areas into regions of poorer soil, yields might well fall or production prove more expensive because more fertilizer was needed.

A key concept in assessing the impact of climatic change is the sensitivity of an agricultural system to variations in climate. This varies markedly over the globe. However, only a very limited number of crops are grown. There are only 30 crops with an annual production of more than 10 million tonnes, and cereals are grown on more than half of the world's arable land. Of the cereals, just three—wheat, maize and rice—account for 80 percent of total production. Rice is the staple diet of 60 percent of the world population. Beef and pork make up about three-quarters of animal production.

Does this concentration of agriculture on so few crops increase its vulnerability to climatic change. Opinions are divided. On the one hand, some crops are clearly vulnerable—rice production, for example, would be likely to suffer in a drier world, and that would affect more than half of the human population. On the other hand, because agriculture has concentrated on so few crops, the numbers of varieties that have been developed are huge, and they are adaptable to a wide range of growing conditions. This makes it easier to adapt to climatic change.

What is clear is that agriculture is more sensitive to climatic variations in some areas than others. In many developing countries, yields and production are low and unstable, food stocks are small, and there is a limited ability to import food. Furthermore, the major exporters and importers of grain are in the temperate regions. All these factors increase the vulnerability of tropical and sub-tropical countries to climatic variation.

In the semi-arid tropics, which occupy 13 percent of the world's land surface, production is finely tuned to what rainfall there is. Small variations in rainfall can produce major changes in production. Furthermore, the resources of farmers there are limited, and easily over-stretched. Even a few years of drought can have dramatic consequences, as was the case during the African famine of the early 1980s. In the tropics, food production is related mainly to the monsoon. Any alteration in its timing or severity can also have a major effect on production. In both the tropics and the sub-tropics, agriculture is all the more vulnerable where carried out on marginal land—as is increasingly common.

Detailed prediction of how climatic change will influence production is hampered by the fact that knowledge of

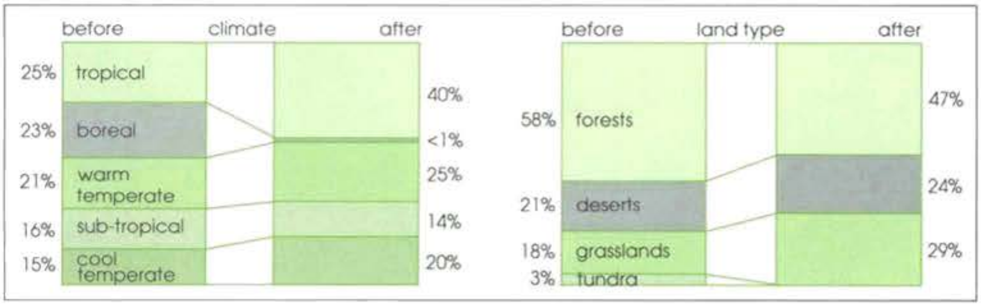


Figure 17 Predicted changes in climates and natural vegetation types caused by a doubling of carbon dioxide levels in the atmosphere. Major effects would include an expansion of grasslands and deserts

what conditions are needed to grow crops is more advanced than the predictive capability of climate models. In other words, if the models could tell us more accurately what climatic conditions could be expected where, good estimates could be made of the resulting agricultural changes. Until models improve, all that can be done is to investigate possible effects of climatic changes that are really only hypothetical.

For example, scientists working at the Institute of Applied Systems Analysis in Austria have investigated one means of estimating the effects on society of a changing climate. Essentially, their technique was to take representative values of temperature, cloudiness and rainfall change for a specific area predicted by a climatic model as a result of doubling carbon dioxide concentrations. A second model was used to relate these changes to changes in yield, and a third model to relate changes in yield to other economic factors.

Their results are not predictions of what will happen in the future but attempts to develop a technique that can be used to assess the social impact of climatic change when atmospheric models improve. However, the results do indicate the broad nature of the changes that future climatic change may produce.

In the central European area of the Soviet Union, the climatic change was taken as a temperature rise of 1.5 °C. Among the effects this would produce would be a 30 percent increase in wheat yield. Additionally, the area suitable for wheat cultivation would increase by 26 percent, providing an overall increase in wheat production of 64 percent.

In Iceland, the atmospheric model forecast a 3.9 °C temperature rise and a 15 percent increase in precipitation. The effects here would also be beneficial, increasing hay yields and the carrying capacities of both grassland and rangeland, and reducing the need for fertilizers and livestock feed. One end result would be an average increase in the carcass weight of lambs, estimated at some 11 percent.

In Finland, the results might be much more variable. Spring wheat yields would increase in the south but barley yields would fall. In the north, where temperatures might rise by as much as 5.0 to 5.5 °C and precipitation double, barley yields would increase substantially.

In Canada's Southern Saskatchewan Province, the temperature was forecast to increase by 3.4 °C and precipitation by 18 percent. This would lower wheat production by 25 percent, causing a knock-on effect throughout the economy. Farm incomes would fall 26 percent, employment drop by 1.9 percent and GDP would fall by 12 percent.

Results like these, of course, assume that the climatic change occurred abruptly. In reality, the process would be slow, allowing farmers time to adjust—for example, by changing their crops or their cultivars as well as their farming techniques. This might allow them to mitigate harmful climatic effects and better exploit potentially beneficial ones.

The impact on ecosystems

The most major change that would occur to ecosystems is that they would be shifted in space. In the high latitudes of the Northern hemisphere, for example, the northern forest limit would shift polewards, as would the northern limit at which grain crops could be grown. Figure 17 shows how one computer model estimates the overall extent of the Earth's major land divisions would change.

One of the least understood areas is how a changing climate alters the mix of plants and animals that make up a natural ecosystem. That they would change seems inevitable. Species that are most responsive to increased carbon dioxide levels, or to warmer temperatures and higher rainfall, would tend to predominate over other species. This, in turn, would influence the animal populations that feed off the plant community. Rangelands, for example, might undergo profound change, with water-sensitive species predominating. Other species might decline in importance or disappear altogether. The life cycles of most plants would probably accelerate, with production of flowers, seeds and fruit occurring at different times, possibly to the inconvenience of the species that pollinate or consume them. If plant growth as a whole were stimulated, soils might become poorer as increasing amounts of minerals from the soil were taken up and captured in the plant biomass.

In semi-arid areas where growth is essentially controlled by the outbreak of fire, such as the chaparral, fuel might accumulate more quickly and fires become more frequent. It is estimated that the 30-40 year fire cycle in San Diego County, United States, might accelerate by 5-10 years. For similar reasons, forest fires might become more frequent. In addition, trees that grew faster and taller might be more susceptible to wind damage.

There is particular concern that climatic change could lead to the disappearance of many rare species. Rare and endangered species are often kept in protected parks in semi-arid areas. If climatic change made the area unsuitable for the species, it is possible that alternative habitats could not be easily found.

Will sea levels rise?

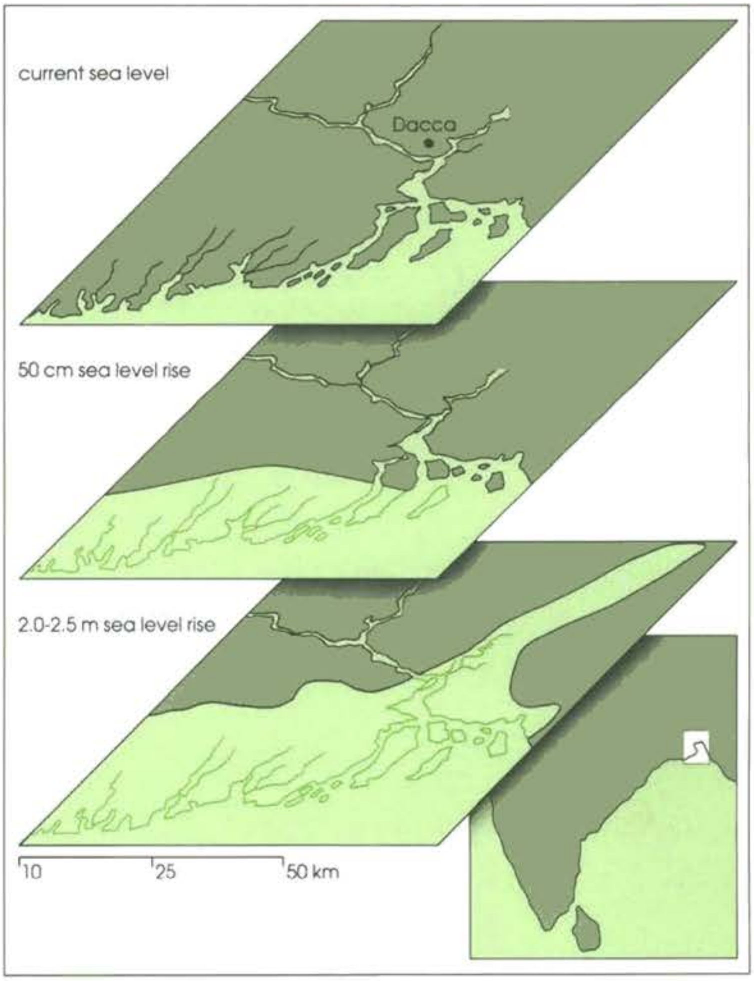
The effects of an increase in average temperature are likely to be felt more strongly in high latitudes than nearer the equator for one simple reason: the areas near the Earth's poles are white. As the Earth warms up, and more snow and ice melt, these areas will reflect less solar radiation and will therefore be subject to exceptional warming.

If this change were sudden and extreme, catastrophic results could ensue. The Arctic Ocean is covered by a layer of ice two to three metres that never melts except at its edges near continental coasts. Under this ice lies relatively warm and salt water. If the polar warming were sufficient to melt the Artic ice, it is possible that as the deeper warmer water mixed with the colder water from which the Arctic ice is formed, conditions would change so much that the Arctic ice never reformed. No one knows what effects that might produce although weather patterns in the whole of the Northern hemisphere would certainly be disrupted. Disappearance of the Arctic ice would also have major strategic and economic implications as it opened up new sea routes.

The Antarctic land mass, of more than 13 million square kilometres, is covered by ice thousands of metres deep. The polar effect here is expected to be smaller than in the Arctic because the Antarctic pack ice round the continent breaks up every summer. However, were the Antarctic ice to melt, world sea levels would rise by an estimated 80 metres, flooding many of the world's major cities and all its ports. A less dramatic result might be if the glaciers on the mountainous western side of the Antarctic were to slide into the sea and melt. This alone would raise sea levels by about six metres, flooding many coastal cities and much productive farmland.

None of these events, it must be stressed, is at all likely in the near future. Melting of the Antarctic ice would take centuries and require temperature rises of the order of 20 °C. And, with only one exception, all climatic models suggest that the Arctic ice will not melt, although it will get thinner. And there are reasons for believing that the greenhouse effect could, at least initially, actually increase the volume of the Antarctic ice.

Figure 18 Even a 50 cm sea level rise would inundate large areas of Bangladesh. A 2.0-2.5 metre rise would reach nearly to the country's capital city



The Antarctic ice cap contains 90 percent of all the land-based ice on the Earth. Its volume is such that if even 1 percent of it were to melt, sea levels would rise by about 80 cm. However, several climatic models suggest that one possible result of a global warming would be to increase the volume of the ice rather than decrease it. This is because there will be increased precipitation in the Antarctic as temperatures rise, resulting in higher snowfall. Thus if temperatures increase by 3 °C and Antarctic precipitation rises 24 percent, the volume of ice in the Antarctic would eventually increase, by somewhat less than 1 percent, leading to a 50 cm fall in sea level. Whether this will happen is far from clear because current climate models are unable to predict events at the poles with any great accuracy.

Nevertheless, a slow rise in sea level is to be expected as carbon dioxide heating progresses. The cause will be not the melting of land-based ice or glaciers but the inevitable expansion of the world's oceans as they warm up. A global warming of 1.5 to 5.5 °C is estimated to cause a sea level rise of between 20 and 165 cm, with a middle range temperature rise producing a sea level about 80 cm higher. Nearly one-third of all human beings live within 60 km of a coastline. A sea level rise of even one metre would be likely to have profound influences on habitation patterns, causing large-scale migrations from low-lying coastal areas. Such changes are, in effect, already underway because sea levels are rising by about 1 mm a year, or 10 cm a century.

Implications for policy

Many bold ideas have been suggested as solutions to the greenhouse problem. The key issue is the burning of fossil fuels which currently provide about 80 percent of world energy. In time, this problem will solve itself because the supply of fossil fuels is limited. But by the time all the Earth's fossil fuels has been burnt, if it ever is, the global warming will be far greater than anything discussed in this publication.

There are four possible ways of dealing with the problem:

- reduce the rate at which fossil fuels are burnt (and at which other industrial processes produce greenhouse gases);
- filter out the greenhouses gases during industrial production and dispose of them elsewhere than in the atmosphere;
- recover greenhouse gases already released into the atmosphere and dispose of them elsewhere; and
- accept the changing environment and adapt to it.

Reducing production

The most obvious way of reducing the greenhouse problem is to use less energy. Only a decade ago, most authorities regarded this as an unworkable solution. Since then, two major rises in the price of oil have had a steadying effect on world energy consumption, and it has been shown that a four percent annual increase in world energy consumption is neither necessary nor inevitable.

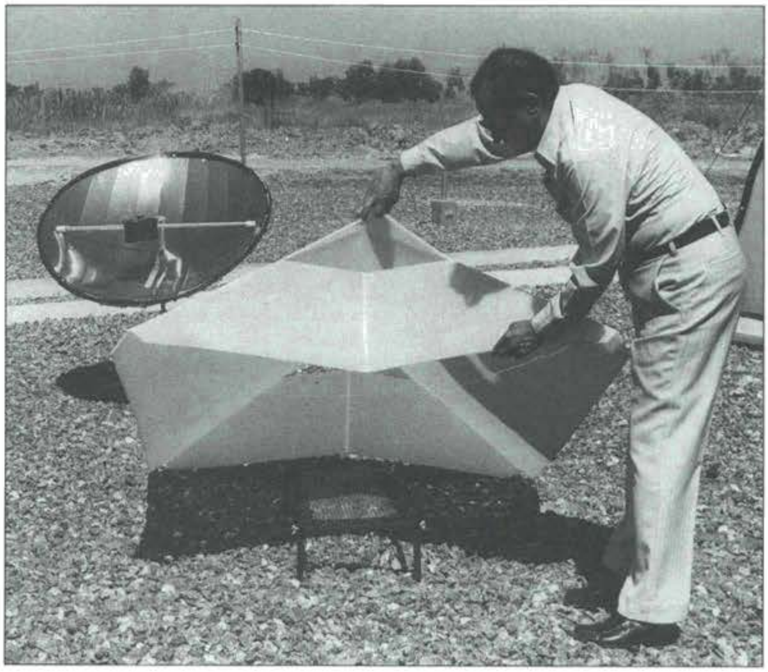
In fact, burning less fossil fuel does not even mean using less energy. Energy could be used much more efficiently than it is now: currently relatively little effort is made to recover waste heat; most buildings could be far better insulated; and energy savings rarely play a major role in policy and planning. As already mentioned, one future scenario suggests that if all available options for energy conservation were taken, carbon emissions could be reduced from 5 Gt now to only about 1 Gt in a few decades time, without delaying development or causing major energy shortages. While this assessment may be optimistic, increasing energy efficiency is certainly a realistic policy option.

A second option is to reduce the amount of fossil fuel burnt and substitute other energy sources that do not release carbon dioxide. The major alternatives are solar energy, wind and wave power, nuclear fission and nuclear fusion. Of these, only nuclear fission offers immediate prospects for major energy substitution.

Solar energy offers good long-term prospects but is under-funded and as yet scarcely economic. Furthermore, even with rapid development, it would be able to supply only a fraction of most countries' needs for power. Solar energy will undoubtedly provide an increasing amount of the power we consume in the future but its development is likely to be too slow to produce a substantial effect on global warming within a few decades time.

Until the late 1960s, nuclear fission was widely regarded as the solution to the energy problem. By the beginning of the 1970s, however, serious doubts had begun to emerge about both the cost and the safety of the nuclear energy programme. In the United States, environmental concern then bought the commissioning of new nuclear reactors to a virtual standstill. Accidents at Three Mile Island in the United States, at the Sellafield nuclear reprocessing centre in the UK and, most recently and dramatically, at Chernobyl in the Soviet Union then undermined public confidence even further. Rightly or wrongly, many people now regard a nuclear energy future as potentially more dangerous than the continued use of fossil fuel, with its accompanying risk of climatic change. Prospects for a rapid expansion of the nuclear energy industry currently appear very remote.

solar energy—underfunded and too late?

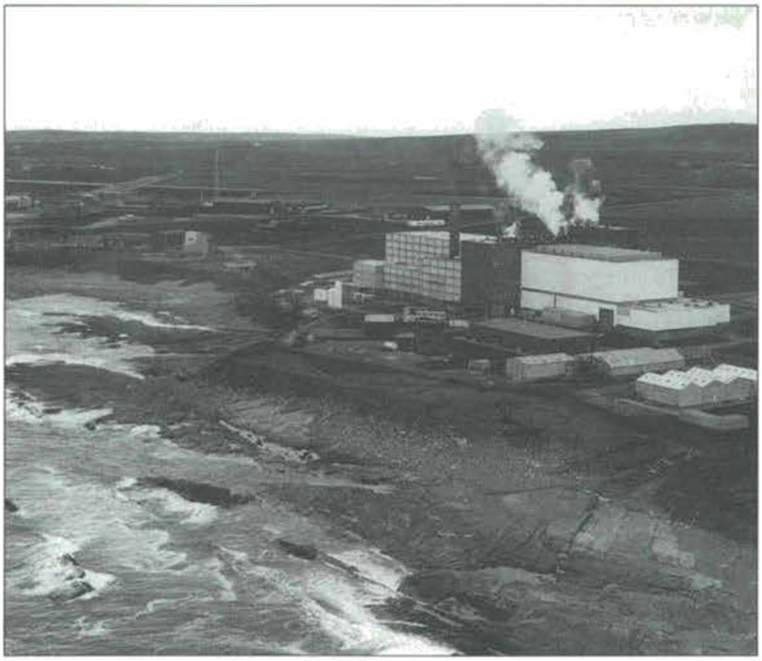


The prospect of being able to control nuclear fusion—by exploiting the power of the hydrogen bomb in a power reactor—is still remote. The first experimental fusion reactor producing useful amounts of power is not now expected until well into the 21st century, at the earliest.

Thus, although the mix of fuels used to supply energy in the future will change, there is unlikely to be any change of sufficient size or speed to make a major impact on the greenhouse problem by, say, the year 2030. Policy options of this type must always be assessed in the light of the relative time scales of both the greenhouse problem and the policy option. A major change in energy sources would take several decades to implement; by then, the first wave of greenhouse warming would be firmly established.

However, some reduction in the greenhouse problem could be achieved by altering the balance between the different fossil fuels used. For the production of a given amount of energy, burning natural gas produces 60 percent of the amount of carbon dioxide that coal does, and burning oil about 80 percent. Synthetic fuels such as methanol, which require energy for their production, produce as much as 1.5 times the amount of carbon dioxide that coal does (unless they are produced using non-fossil fuel energy sources). Broadly, then, the more we rely on natural gas, and to a lesser extent oil, and the less we rely on coal and synthetic fuels, the longer will major climatic changes be delayed.

In about 50 years time, these proposals will be relevant only to one half of the problem. The other half of global warming is likely to be caused by gases other than carbon dioxide. It seems likely that CFC production and use probably will be further limited in some way in the next decade. Action here is relatively easy, particularly in view of the damaging effect of the CFCs on the ozone layer as well as on climate. What could be done about future levels of nitrous oxide and methane is less clear, however, because the exact reasons for the current increases of these gases in the atmosphere are not well understood. When they are, it may be possible to isolate those activities that are mainly responsible for the increases, and curtail them.



nuclear power—a dangerous alternative?

Filtering out the greenhouse gases

Many schemes have been suggested for preventing carbon dioxide reaching the atmosphere at all. Technically, the process is possible. One such scheme envisaged that carbon dioxide would be filtered out of the effluent from power stations, converted into a transportable carbon compound, delivered by ship to the Straits of Gibraltar, and there pumped to the ocean floor. Currents leading from the Mediterranean to the Atlantic would then disperse the carbon into the ocean where it would dissolve *(see Figure 19)*.

While the oceans have the capacity to absorb considerable quantities of carbon dioxide (as do depleted oil and gas wells and salt caverns), the costs of such a scheme currently outweigh the perceived danger of a small global warming.

Whether or not such a view is correct, the prospect that any scheme of this kind will in fact be implemented is small because of the cost. One US study has estimated that to remove 90 percent of the carbon dioxide from the effluent of power stations, and then store it, would double the capital costs of power stations, and increase the cost of electricity by a factor of 1.5 to 2. In addition, 10-20 percent of the power stations' output would be needed to power the cleaning up process.

Even regardless of cost, implementation of such a scheme on a global basis could take many decades and would therefore do little to prevent the global warming forecast over the next few decades. However, it might ameliorate the situation later in the next century.

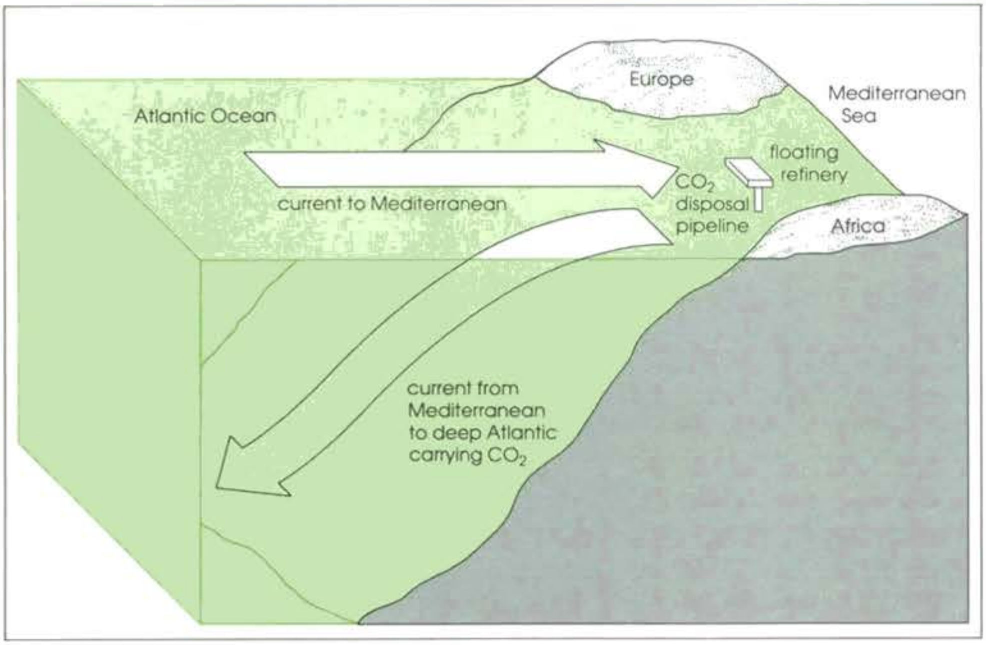


Figure 19 One proposed solution for disposing of carbon dioxide filtered from power station emissions would involve transporting it by ship to the Straits of Gibraltar, piping it to the sea floor, and allowing underwater currents to transport it to the Atlantic

Filtering out greenhouse gases other than carbon dioxide does not seem realistic, particularly because they are not released from large-scale sources but from huge numbers of small ones. In contrast, about half the carbon dioxide entering the atmosphere comes from large power stations.

Recovering the greenhouse gases

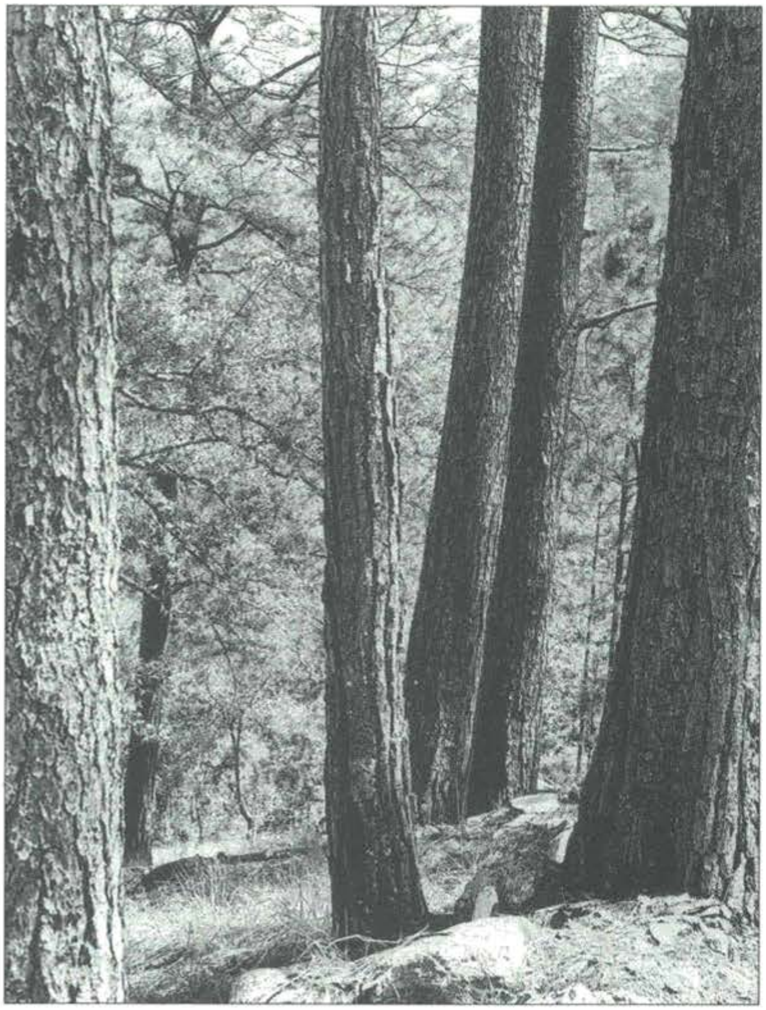
In theory, this idea is not as preposterous as it sounds. During the 1970s, a number of scientists proposed the idea of a massive reforestation of the Earth, coupled with a change to a wood economy in which materials such as concrete, aluminium and plastics were replaced by timber. This would enlarge the biological carbon sink, with the result that a greater proportion of carbon in the carbon cycle would find its way into the Earth's biomass rather than into the atmosphere. Such a scheme has many obvious environmental advantages in addition to reducing the threat of global warming.

Unhappily, even though the pace of reforestation is likely to increase in both developing and developed countries over the next few decades, the scale of the operation is not likely to have a major effect on greenhouse warming. Planting trees is expensive and slow (in contrast to cutting them down, which is quick and cheap). And by the time the new trees had matured, the first wave of climatic change would have already occurred.

In addition, the scale of the operation now appears unfeasible. Although the conversion of forest land to agriculture was originally responsible for much of the early increase in carbon dioxide levels, it has now assumed decreasing importance compared to fossil fuel burning—and will continue to do so. Current levels of deforestation—assuming that all the timber is burnt—produce only about one-fifth as much carbon dioxide as fossil fuel burning. An area about the size of France would have to be deforested annually if forest clearing were to contribute as much carbon dioxide to the atmosphere as fossil fuel burning. It follows that a much larger area than France would have to be reforested annually to 'mop up' the carbon dioxide from fossil fuel burning (much larger because trees take decades to mature). To offset a doubling of carbon dioxide levels would require a doubling of the amount of vegetation on the Earth.

This, of course, is not an argument for *not* reforesting extensive areas of the Earth. It is simply a matter of political and scientific reality that a reforestation programme of appropriate scale could not be executed in time, and its effects would in any case only reduce rather than eliminate the global warming. In fact, the reforestation solution was proposed before the role of greenhouse gases other than carbon dioxide was fully appreciated. Because these gases seem likely to produce a global warming of about the same size as carbon dioxide itself, even the limited effectiveness of the reforestation solution is reduced by about a half.

If there is not room to accommodate the carbon in the atmosphere on the Earth's land surface, could it not be swept up into the oceans instead? In theory, it could. One way of doing this would be to accelerate the biological pump that extracts carbon dioxide from the air and converts it into carbonates in the oceans. The main actors in this pump are the marine plankton that, through photosynthesis, turn carbon dioxide into other compounds that sink to the ocean floor when the plankton die. A large-scale fertilization of the oceans would speed up this process. What it would cost, how effective it would be, and what might be its side effects are largely unknown. This policy option, as yet, remains in the realm of science fiction—as, indeed, do related possibilities of modifying the climate to induce a cooling to counteract the prospective warming, for example by seeding the atmosphere with small particles to increase its reflectivity.



more forests might help sweep the atmosphere clean of carbon dioxide—but an area larger than France would have to be planted annually to compensate for current rates of fossil fuel burning

Adapting to change

Discussions of the effects of climatic change often assume that such a change could arrive swiftly. Estimates have been made, for example, that purport to show that a sudden 2 °C temperature rise might reduce grain yields in northern temperate zones by as much as 17 percent. Such estimates can be very misleading because agriculture is continually adapting to climatic variation, and does so relatively quickly: it takes only about a decade to develop and introduce a new crop variety, for example.

The global warming produced by the greenhouse gases will arrive slowly—and, indeed, may have even begun. By the time there is a rise of average temperature of even a degree or two, agriculture will have already adapted to most of this rise. Different crops, different varieties and different farming techniques will all help absorb the impact of the change. The world system of agricultural trade is also capable of adapting to change, with different countries exporting and importing different quantities of different commodities. However, adaptation may be much more problematic in marginal food-producing areas where production is notoriously sensitive to climatic change, and the rate of change of agricultural technology very slow.

Similarly, people are likely to adapt relatively well to a changing climate—for example, by better control of the microclimates inside their buildings. It is even possible to adapt to changes in sea level of the scale envisaged. The Dutch, after all, have been living some 5 metres below sea level for centuries, thanks to their elaborate system of sea dikes. Again, the problem is likely to be less acute for the developed countries than for low-lying developing states such as Bangladesh, where major flooding is already an almost perennial problem.

Assessing practical policies

The range of options open to policy makers is thus fairly clear. What is much less clear, however, is how effective they would would be, what they would cost and what might be their side effects. Nor has any systematic study of the risks involved yet been undertaken. For example, although scientists have estimated what they think will be the size of the global warming at a given date, it would also be instructive to learn what is the risk that the warming would be much greater. Such a risk assessment could then be better balanced against the risks and costs involved in adopting specific policy options—for example, expanding the nuclear energy programme or reducing the production of CFCs.

Essentially, combatting the greenhouse problem now involves two further, major steps: first, assessing the costs, risks and side effects of the available options; and, secondly, having decided on the available options formulating an international process through which effective action can be taken to lessen the danger. Scientific studies on the first of these steps are already underway but before any policy or set of policies is espoused there will have to be extensive discussion with policy makers at the international level. Action on a global problem such as the greenhouse effect cannot be taken by any individual nation or group of nations.

The process by which international action could be agreed raises severe problems that are not likely to be overcome in the near future. Many of these problems involve the 'North-South' arguments that have produced stalemates on other global issues in the past. For example, while developed countries might be willing to curtail their use of fossil fuels in the future, developing ones—which consume far less fuel—would be much less likely to agree to any such restrictions. Furthermore, representatives of some developing countries have already made it clear that, on the basis of current knowledge, the climatic changes likely to occur as a result of global warming could well be welcomed by them. Temperature rises would probably be small in tropical and sub-tropical regions, and increased precipitation could prove beneficial in several developing areas.

The mechanisms by which such discussions could begin has yet to be decided. Fortunately, however, there is an effective model in a body known as the Coordinating Committee on the Ozone Layer, which was set up by UNEP in the 1970s to stimulate research on the possible extent of future ozone depletion and its effects on society. This body has played a major supporting role in the preparation of a Convention for the Protection of the Ozone Layer by providing scientific advice to the group of legal and technical experts established by UNEP to elaborate a draft convention. The Convention was agreed to in March 1985, and has since been signed by many states. A Protocol regulating the emission and/or production of chlorofluorocarbons may soon be added to it. It may be that the creation of a Coordinating Committee on the Earth's Climate could achieve similar results.

These are issues for tomorrow's agenda. But, if this agenda is to be debated and acted on in time, it is important that the scientific facts on which to base future decisions be rapidly established. Far more is known about the greenhouse effect, and its consequences, than a decade ago. As detailed regional assessments of climatic change are made over the next few years, sufficient knowledge should be generated to move the centre of action away from the research laboratory and onto the policy maker's desk.

Sources

Breuer, G. *Air in Danger: ecological perspectives of the atmosphere.* Cambridge, Cambridge University Press, 1980.

Health Council of the Netherlands. *Part one report on the CO_2 problem.* The Hague, Government Publishing Office, 1984.

Inadvertent Climate Modification. Cambridge, Massachusetts, MIT Press, 1971, Report of the Study of Man's Impact on Climate.

International Council of Scientific Unions, United Nations Environment Programme and World Meteorological Organization. *Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of other Greenhouse Gases in Climate Variations and Associated Impacts*, Villach, Austria, 9-15 October 1985. Geneva, WMO, 1986.

Kates, Robert W., with Ausubel, Jesse H., and Berberian, Mimi (eds.). *Climate Impact Assessment.* London, John Wiley, 1985 (SCOPE 27).

MacCracken, Michael C., and Luther, Frederick M. (eds.). *The Potential Climatic Effects of Increasing Carbon Dioxide.* Washington DC, US Department of Energy, 1985 (DOE/ER-0237).

Seidel, S., Tirpak, D., and Hoffman, J. S. *Potential health and environmental effects of ozone depletion and climate change.* Paper prepared for UNEP workshop on Protecting the Stratospheric Ozone Layer, Leesburg, Virginia, September 8-12, 1986.

Strain, Boyd R., and Cure, Jennifer D. *Direct effects of increasing carbon dioxide on vegetation.* Washington DC, US Department of Energy, 1985 (DOE/ER-0238).

Titus, James G. (ed.). *Effects of changes in stratospheric ozone and global climate: Volume 1, Overview.* Proceedings of the International Conference on Health and Environmental Effects of Ozone Modification and Climate Change, 16-20 June 1986. Nairobi and Washington DC, United Nations Environment Programme and United States Environmental Protection Agency, 1986.

Trabalka, John R. *Atmospheric carbon dioxide and the global carbon cycle.* Washington DC, US Department of Energy, 1985 (DOE/ER-0239).

Tromp, S. W. *Biometeorology: the impact of the weather and climate on humans and their environment.* London, Heyden, 1980.

United Nations Environment Programme. *Possible Effects of Man's Activities on the Ozone Layer and Climate.* Nairobi, UNEP, 1986, UNEP Policy Support Document.

Watson, R. T., Geller, M. A., Stolarski, R. S., and Hampson, R. F. *Present State of Knowledge of the Upper Atmosphere: processes that control ozone and other climatically important trace gases.* NASA, Washington D.C., 1986, NASA Reference Publication 1162.

Acknowledgements

Photographs on pages 5, 25, 34, 35 and 37 are courtesy of the Food and Agriculture Organization of the United Nations.