Global Warming

THE COMPLETE BRIEFING

THIRD EDITION

John Houghton

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The Complete Briefing
Third Edition

Global warming and the resulting climate change are among the most serious environmental problems facing the world community. *Global Warming: The Complete Briefing* is the most comprehensive guide available to the subject. A world-renowned expert, Sir John Houghton explores the scientific basis of global warming and the likely impacts of climate change on human society, before addressing the action that could be taken by governments, by industry and by individuals to mitigate the effects. The first two editions received excellent reviews, and this completely updated new edition will prove to be the best briefing the student or interested general reader could wish for.

SIR JOHN T. HOUGHTON CBE, FRS is a former Chairman of the Scientific Assessment Working Group of the Intergovernmental Panel on Climate Change, Chairman of the UK's Royal Commission on Environmental Pollution, Vice President of the World Meteorological Organization, President of the Royal Meteorological Society, and Professor of Atmospheric Physics at Oxford University. He was Chief Executive of the UK Meteorological Office from 1983 to his retirement in 1991. As well as the previous editions of this book, he is author of *The Physics of Atmospheres* (Cambridge University Press, in three editions), and has published numerous research papers and contributed to many influential research documents. Sir John and his wife Sheila live in Wales.

From reviews of previous editions

'It is difficult to imagine how Houghton's exposition of this complex body of information might be substantially improved upon . . . Seldom has such a complex topic been presented with such remarkable simplicity, directness and crystalline clarity . . . Houghton's complete briefing is without doubt the best briefing the concerned citizen could hope to find within the pages of a pocketable book.'

John Perry, *Bulletin of the American Meteorological Society*

'I can recommend (this book) to anyone who wants to get a better perspective on the topic of global warming . . . a very readable and comprehensive guide to the changes that are occurring now, and could occur in the future, as a result of human action . . . brings the global warming debate right up to date . . . Read Houghton's book if you really want to understand both the scientific and political issues involved.'

William Harston, *The Independent*

'. . . precise account of the science, accompanied by figures, graphs, boxes on specific points, and summaries at the end of each chapter, with questions for students . . . ranges beyond the science into the diplomacy, politics, economics and ethics of the problem, which together present a formidable challenge to human understanding and capacity for action.'

Sir Crispin Tickell, *The Times Higher Education Supplement*

'. . . a widely praised book on global warming and its consequences.'

The Economist

'. . . an interesting account of the topic for the general reader.'

Environmental Assessment

'. . . very thorough and presents a balanced, impartial picture.'

Jonathan Shanklin, *Journal of the British Astronomical Association*

'I would thoroughly recommend this book to anyone concerned about global warming. It provides an excellent essentially non-technical guide on scientific and political aspects of the subject. It is an essential briefing for students and science teachers.'

Tony Waters, *The Observatory*

'For the non-technical reader, the best program guide to the political and scientific debate is John Houghton's book *Global Warming: The Complete Briefing*. With this book in hand you are ready to make sense of the debate and reach your own conclusions.'

Alan Hecht, *Climate Change*

'This is a remarkable book . . . It is a model of clear exposition and comprehensible writing . . . Quite apart from its value as a background reader for science teachers and students, it would make a splendid basis for a college general course.'

Andrew Bishop, *Association for Science Education*

'*Global Warming* remains the best single-volume guide to the science of climate change.'

Greg Terrill, *Times Literary Supplement*

'This very readable and informative book is valuable for anyone wanting a broad overview of what we know about climate change, its potential impacts on society and the natural world, and what could be done to mitigate or adapt to global warming. To this end, discussion questions are included at the end of each chapter. The paperback edition is especially good value . . . Houghton's compact book is an accessible, well-researched, and broadly based introduction to the immensely complicated global warming problem.'

Dennis L. Hartmann, Department of Atmospheric Sciences, University of Washington, Seattle, USA

'I have no hesitation in endorsing this important book.'

Wilfrid Bach, *International Journal of Climatology*

'. . . a useful book for students and laymen to understand some of the complexities of the global warming issue. Questions and essay topics at the end of each chapter provide useful follow-up work and the range of material provided under one cover is impressive. At a student-friendly price, this is a book to buy for yourself and not rely on the library copy.'

Allen Perry, *Holocene*

'In summary I would thoroughly recommend this book to anyone concerned about global warming. It provides an excellent non-technical guide on scientific and political aspects of the subject. It is an essential briefing for students and science teachers.'

Tony Waters, *Weather*

'This book is one of the best I have encountered, that deal with climate change and some of its anthropogenic causes. Well written, well organised, richly illustrated and referenced, it should be required reading for anybody concerned with the fate of our planet.'

Elmar R. Reiter, *Meteorology and Atmospheric Physics*

'Sir John Houghton is one of the few people who can legitimately use the phrase "the complete briefing" as a subtitle for a book on global warming . . . Sir John has done us all a great favour in presenting such a wealth of material so clearly and accessibly and in drawing attention to the ethical underpinnings of our interpretation of this area of environmental science.'

Progress in Physical Geography

'. . . this complete briefing on global warming is remarkably factual and inclusive. Houghton's concern about planet Earth and its people blends well with this his hopes for global cooperation in concert with the spirit of the Intergovernmental Panel on Climate Change.'

Choice

'Throughout the book this argument is well developed and explained in a way that the average reader could understand especially because there are many diagrams, tables, graphs and maps which are easy to interpret.'

SATYA

'. . . this book is the most comprehensive guide available. Ignore it at your peril.'

The Canadian Field-Naturalist

Global Warming

The Complete Briefing

THIRD EDITION

Sir John Houghton

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**To my grandchildren,
Daniel, Hannah, Esther, Max, Jonathan, Jemima and Sam and
their generation**

Contents

Figures

SI unit prefixes

Quantity	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n

Chemical symbols

CFCs	chlorofluorocarbons
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	molecular hydrogen
HCFCs	hydrochlorofluorocarbons
H_2O	water
N_2	molecular nitrogen
N_2O	nitrous oxide
NO	nitric oxide
NO_2	nitrogen dioxide
O_2	molecular oxygen
O_3	ozone
OH	hydroxyl radical
SO_2	sulphur dioxide

Preface to the First Edition

Climate change and global warming are well up on the current political agenda. There are urgent questions everyone is asking: are human activities altering the climate? Is global warming a reality? How big are the changes likely to be? Will there be more serious disasters; will they be more frequent? Can we adapt to climate change or can we change the way we do things so that we can slow down the change or even prevent it occurring?

Because the Earth's climate system is highly complex, and because human behaviour and reaction to change is even more complex, providing answers to these questions is an enormous challenge to the world's scientists. As with many scientific problems only partial answers are available, but our knowledge is evolving rapidly, and the world's scientists have been addressing the problems with much energy and determination.

Three major pollution issues are often put together in people's minds: global warming, ozone depletion (the ozone hole) and acid rain. Although there are links between the science of these three issues (the chemicals which deplete ozone and the particles which are involved in the formation of acid rain also contribute to global warming), they are essentially three distinct problems. Their most important common feature is their large scale. In the case of acid rain the emissions of sulphur dioxide from one nation's territory can seriously affect the forests and the lakes of countries which may be downwind of the pollution. Global warming and ozone depletion are examples of global pollution – pollution in which the activities of one person or one nation can affect all people and all nations. It is only during the last thirty years or so that human activities have been of such a kind or on a sufficiently large scale that their effects can be significant globally. And because the problems are global, all nations have to be involved in their solution.

The key intergovernmental body which has been set up to assess the problem of global warming is the Intergovernmental Panel on Climate Change (IPCC), formed in 1988. At its first meeting in November of that year in Geneva, the Panel's first action was to ask for a scientific report so that, so far as they were known, the scientific facts about global warming could be established. It was imperative that politicians were given a solid scientific base from which to develop the requirements for action.

That first scientific report was published at the end of May 1990. On Monday 17 May I presented a preview of it to the then British Prime Minister, Mrs Margaret Thatcher, and members of her Cabinet at 10, Downing Street in London. I had been led to expect many interruptions and questions during my presentation. But the thirty or so Cabinet members and officials in the historic Cabinet room heard me in silence. They were clearly very interested in the report, and the questions and discussion afterwards demonstrated a large degree of concern for the world's environmental problems.

Since then the interest of many political leaders has been aroused – as has been shown by their attendance at two important world conferences concerned with global warming: the Second World Climate Conference in Geneva in 1990 and the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992. The Rio conference with over 25 000 people attending the main sessions and the many side meetings, was the largest conference ever held. Never before had a single conference seen so many of the world's leaders, and for that reason it is often referred to as the Earth Summit.

Much of the continuing assessment of climate change has been focused on the IPCC and its three working groups dealing respectively with science, impacts and response strategies. The IPCC's first report published in 1990 was a key input to the international negotiations which prepared the agenda for the UNCED Conference in Rio de Janeiro; it was that IPCC assessment which provided much of the impetus for the Framework Convention on climate change signed at Rio by over 160 countries. As chairman or co-chairman of the Science Working Group I have been privileged to work closely with hundreds of scientific colleagues in many countries who readily gave of their time and expertise to contribute to the IPCC work.

For this book I have drawn heavily on the 1990 and 1992 reports of all three working groups of IPCC. Further, in putting forward options for action I have followed the logic of the Climate Convention. What I have said I believe to be consistent with the IPCC reports and with the implications of the Climate Convention. However, I must also emphasise that the choice of material and any particular views I put forward are entirely my own and should in no way be construed as the views of the IPCC.

During the preparation of both IPCC reports so far there has been considerable scientific debate about just how much can be said about likely climate change next century. Some researchers initially felt that the uncertainties were such that scientists should refrain from making any estimates or predictions for the future. However, it soon became clear that scientists have a responsibility to communicate the best possible information about the likely magnitude of climate change, along with clear statements of the assumptions made and the level of uncertainty in the estimates. Like weather forecasters, their results will not be entirely accurate, but can provide useful guidance.

Many books have been published on global warming. This book differs from the others because I have attempted to describe the science of global warming, its impacts and what action might be taken in a way which the intelligent non-scientist can understand. Although there are many numbers in the book – I believe the quantification of the problem to be very important – there are no mathematical equations. I have also used the minimum of jargon in the main text. Some technical explanations which would be of interest to the scientifically trained are included in some of the boxes. Others contain further material of specific interest.

I am grateful to many who have helped me with the provision and preparation of particular material for this book and to those who have read and helpfully commented on my drafts. There have been those who have been involved with the IPCC: Bert Bolin, the IPCC Chairman, Gylvan Meira Filho, my co-chairman on the IPCC Science Working Group, Robert Watson, co-chairman of the IPCC Working Group on Impacts and Response Strategies, Bruce Callander, Chris Folland, Neil Harris, Katherine Maskell, John Mitchell, Martin Parry, Peter Rowntree, Catherine Senior and Tom Wigley. Others I wish to thank are Myles Allen, David Carson, Jonathan Gregory, Donald Hay, David Fisk, Kathryn Francis, Michael Jefferson, Geoffrey Lean and John Twidell. The staff at Lion Publishing, Rebecca Winter, Nicholas Rous and Sarah Hall, have been most helpful in preparing the book for publication, especially in ensuring that it is as attractive and readable as possible. Finally, I owe an especial debt to my wife, Sheila, who gave me strong encouragement to write the book in the first place, and who has continued her encouragement and support through the long hours of its production.

Preface to the Second Edition

Since the publication of the first edition nearly three years ago, interest in the issue of Global Warming and concern about it has continued to grow. The Framework Convention on Climate Change (FCCC) agreed at the Earth Summit in 1992 has been ratified and machinery for its implementation is gradually being developed. At the end of 1995, the IPCC produced a further comprehensive report updating the 1990 report. Although the main conclusions have not changed, much has been added to the detail of our knowledge regarding all aspects of the issue, the science, the impacts and the possible response. This revised edition takes into account this further information from the 1995 IPCC reports.

In the first edition I included a chapter, Chapter 8, with the heading 'Why should we be concerned?' which addresses the question of the responsibility of humans for the Earth and for looking after the environment. In it I presented something of the basis for my personal motivation as a Christian for being concerned with environmental problems. Although I believe that it is important that science is presented in the broad context of human values, I realised that the inclusion of such a chapter was something of a departure and wondered how it would be received.

Some have expressed surprise that in the middle of a science book, there should be, unusually, a chapter of this kind which deals with ethical and religious issues. However, it has been pleasing that scientific colleagues and reviewers of the book have referred favourably to the chapter stressing the value and importance of placing environmental science in the context of the reasons for its pursuit. For instance, John Perry, in the *Bulletin of the American Meteorological Society*, writes:

> Many scientists, including avowed agnostics such as myself, will find this forth-right declaration of religious belief and divine purpose a bit startling in an otherwise rigorously scientific volume. However, in a line of argument that I have no difficulty whatever in supporting, Houghton demonstrates that the domains of science and religion are simply complementary ways of looking at truth. The former deals with how the world works and the latter with why. In Houghton's framework, we and the earth are each other's reasons for existence in a divine plan that we must

> struggle to understand but must inescapably follow. Thus, Houghton holds that we have no choice but to care for the earth solicitously as its 'gardeners' in a 'partnership with God'. His lucid precis of the complex factual substance of global warming is an authoritative guide to the issue's scientific dimensions; his inspiring synthesis of science, faith and stewardship is an even more illuminating handbook to its moral and ethical dimensions. Together, they constitute a uniquely valuable Baedeker to one of the most important issues of our science and our time.

In revising Chapter 8 for this edition, I have been somewhat more objective and less personal – which I felt was more appropriate for student readers from a wide range of disciplines, for whom the edition is particularly suited. As a didactic aid I have also included a number of problems and questions for discussion at the end of all the chapters.

Some of my colleagues sometimes comment on how formidable is the task of sewardship of the Earth feeling that it is perhaps beyond the capability of the human race to tackle it adequately. I feel optimistic about it, however, for three main reasons. Firstly, I have seen how the world's scientists, coming from very different countries, cultures and backgrounds, have worked closely and responsibly in the IPCC to provide a consensus presentation of the science of global warming. Secondly, the technologies required to provide for greater efficiency in the use of fossil fuels and for their replacement with renewable sources of energy are available and, when developed on the necessary scale, also affordable. Thirdly, my belief in God's commitment to the material world coupled with his offer of partnership in caring for it, makes stewardship of the Earth an especially exciting and challenging activity.

In the preparation of this revised volume I wish to express again my gratitute to the scientific colleagues with whom I have worked in the ongoing activity of the IPCC and from whom I have learnt much. My thanks are also due to John Twidell and Michael Banner who have commented on particular chapters, and to Catherine Flack, Matt Lloyd and other staff of the Cambridge University Press for their competence, courtesy and assistance in the preparation of the book.

John Houghton

1997

Preface to the Third Edition

Since the Second Edition seven years ago, research and debate on the issue of human-induced climate change have grown at a rapidly increasing pace. Observations of climate during this period have provided further information about the warming Earth and there has been substantial improvement in the models that simulate both past and future climate. Although the main messages regarding the fact of human-induced climate change and its impact have not changed significantly (on the whole they have been strengthened) more detailed understanding has been achieved regarding the basic science (including the uncertainties), the likely impacts and the imperative for action. Hence the need to update this book.

In 2001 the Intergovernmental Panel on Climate Change (IPCC) published its Third Assessment Report–even more thorough and comprehensive than the first two. As co-chair of the scientific assessment working group for all three of the IPCC reports, I have been privileged to be a part of the IPCC process, which has been so effective in informing the scientific community. Then, through that community, information has been spread to decision makers and others regarding what is known about climate change with some degree of certainty and also about the areas where there remains much uncertainty. I have leant heavily on the IPCC 2001 Report in revising this text and wish to express my deep gratitude to those many IPCC colleagues with whom I have worked and from whom I have learnt so much. I have also benefited greatly from my association with the UK Hadley Centre for Climate Prediction and Research, which has become the world's premier centre for climate modelling research.

My especial thanks are due to those who have provided me with particular new material; Peter Cox, Chris Jones, Colin Prentice and Jo House for Chapter 3; Chris Folland and Alan Dickinson for Chapters 4 and 5; Tim Palmer and Jonathan Gregory for Chapter 6; Martin Parry and Rajendra Pachauri for Chapter 7; Stephen Briggs for material regarding Envisat for Chapter 9; Aubrey Meyer for Chapter 10; Mark Akhurst, Andre Romeyn, Robert Kleiburg, Gert Jan Kramer, Chris West, Peter Smith and Chris Llewellyn Smith for Chapter 11; and William Clark for Chapter 12. John Mitchell, Terry Barker and Susan Baylis kindly read

and commented on some of the draft chapters. I am also particularly grateful to David Griggs, Geoffrey Jenkins, Philippe Rekacewicz and Paul van der Linden who assisted with the sourcing and preparation of the figures. Finally, I wish to thank Matt Lloyd, Carol Miller, Sarah Price and other staff of Cambridge University Press who have carefully steered the book through its gestation and production.

In January of this year I attended the World Economic Forum in Davos and engaged in discussion and debate regarding global warming and climate change. Nearly everyone there accepted the fact of climate change due to human activities and the need for action to reduce greenhouse gas emissions in order to reduce its impact. However, many participants knew little of the likely impacts of climate change or of the extent of the action required to address it; they just believed that it was one of those problems that would have to be addressed sometime. I hope that this book will assist in making the necessary information more readily available and so help to provide the foundation for the urgent action that is required.

John Houghton

Chapter 1
Global warming and climate change

The phrase 'global warming' has become familiar to many people as one of the important environmental issues of our day. Many opinions have been expressed concerning it, from the doom-laden to the dismissive. This book aims to state the current scientific position on global warming clearly, so that we can make informed decisions on the facts.

Is the climate changing?

In the year 2060 my grandchildren will be approaching seventy; what will their world be like? Indeed, what will it be like during the seventy years or so of their normal life span? Many new things have happened in the last seventy years that could not have been predicted in the 1930s. The pace of change is such that even more novelty can be expected in the next seventy. It is fairly certain that the world will be even more crowded and more connected. Will the increasing scale of human activities affect the environment? In particular, will the world be warmer? How is its climate likely to change?

Before studying future climate changes, what can be said about climate changes in the past? In the more distant past there have been very large changes. The last million years has seen a succession of major ice ages interspersed with warmer periods. The last of these ice ages began to come to an end about 20 000 years ago and we are now in what is called an interglacial period. Chapter 4 will focus on these times far back in the past. But have there been changes in the very much shorter period of living memory – over the past few decades?

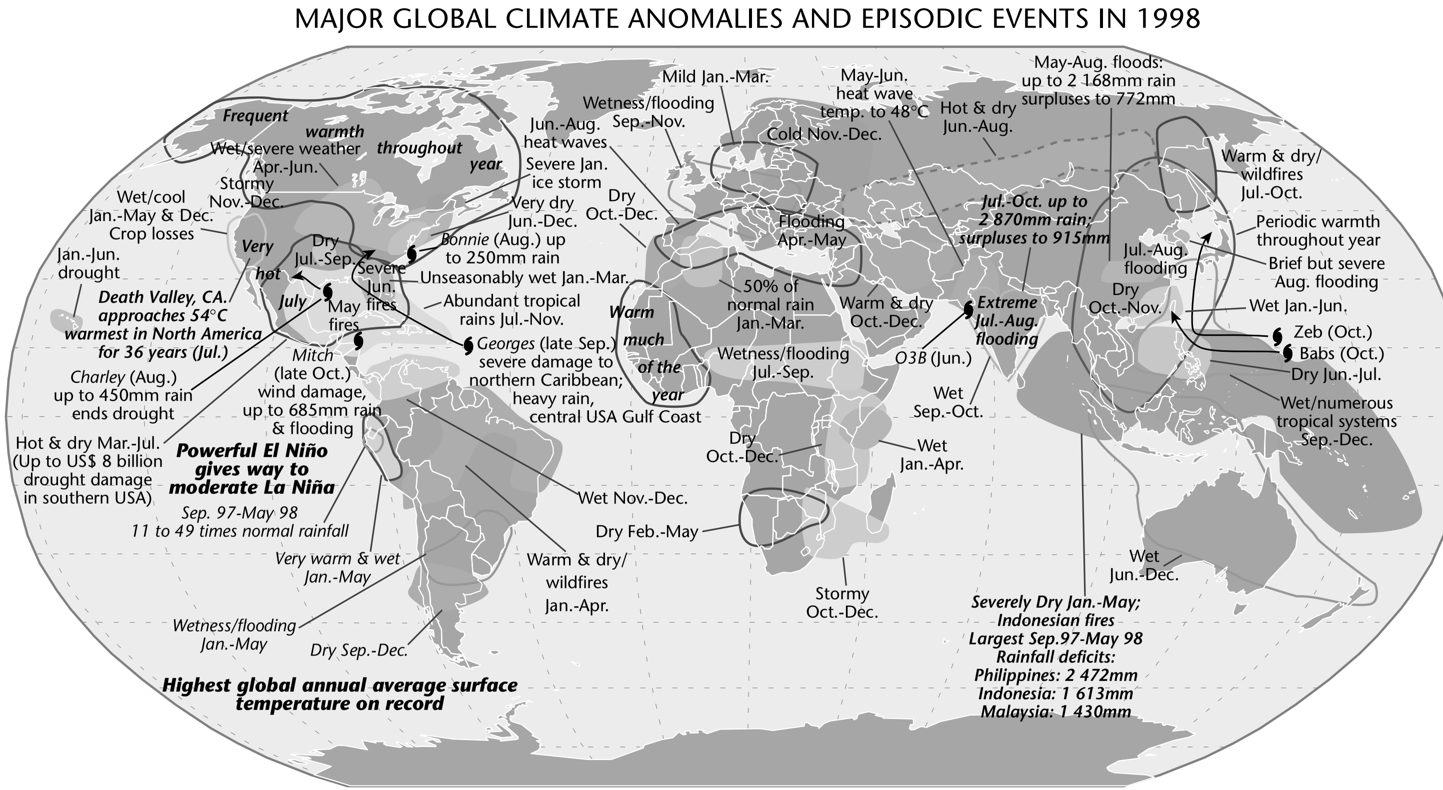
Variations in day-to-day weather are occurring all the time; they are very much part of our lives. The climate of a region is its average weather over a period that may be a few months, a season or a few years. Variations in climate are also very familiar to us. We describe summers as wet or dry, winters as mild, cold or stormy. In the British Isles, as in many parts of the world, no season is the same as the last or indeed the same as any previous season, nor will it be repeated in detail next time round. Most of these variations we take for granted; they add a lot of interest to our lives. Those we particularly notice are the extreme situations and the climate disasters (for instance, Figure 1.1 shows the significant climate events and disasters during the year 1998). Most of the worst disasters in the world are, in fact, weather- or climate-related. Our news media are constantly bringing them to our notice as they occur in different parts of the world – tropical cyclones (called hurricanes or typhoons), wind-storms, floods, tornadoes and droughts whose effects occur more slowly, but which are probably the most damaging disasters of all.

The remarkable last decades of the twentieth century

The 1980s and 1990s were unusually warm. Globally speaking, the decades have been the warmest since accurate records began somewhat over a hundred years ago and these unusually warm years are continuing into the twenty-first century. In terms of global average near-surface air temperature, the year 1998 was the warmest in the instrumental record and the nine warmest years in that record have occurred since 1990.

The period has also been remarkable (just how remarkable will be considered later) for the frequency and intensity of extremes of weather and climate. For example, periods of unusually strong winds have been experienced in western Europe. During the early hours of the morning of 16 October 1987, over fifteen million trees were blown down in south-east England and the London area. The storm also hit Northern France, Belgium and The Netherlands with ferocious intensity; it turned out to be the worst storm experienced in the area since 1703. Storm-force winds of similar or even greater intensity but covering a greater area of western Europe have struck since – on four occasions in 1990 and three occasions in December 1999.[1]

But those storms in Europe were mild by comparison with the much more intense and damaging storms other parts of the world have experienced during these years. About eighty hurricanes and typhoons – other names for tropical cyclones – occur around the tropical oceans each year,



Source: Climate Prediction Center, NOAA, USA

Figure 1.1 Significant climate anomalies and events during 1998 as recorded by the Climate Prediction Center of the National Oceanic and Atmosphere Administration (NOAA) of the United States.

familiar enough to be given names. Hurricane Gilbert that caused devastation on the island of Jamaica and the coast of Mexico in 1988, Typhoon Mireille that hit Japan in 1991, Hurricane Andrew that caused a great deal of damage in Florida and other regions of the southern United States in 1992 and Hurricane Mitch that caused great devastation in Honduras and other countries of central America in 1998 are notable recent examples. Low-lying areas such as Bangladesh are particularly vulnerable to the storm surges associated with tropical cyclones; the combined effect of intensely low atmospheric pressure, extremely strong winds and high tides causes a surge of water which can reach far inland. In one of the worst such disasters in the twentieth century over 250 000 people were drowned in Bangladesh in 1970. The people of that country experienced another storm of similar proportions in 1999 as did the neighbouring Indian state of Orissa also in 1999, and smaller surges are a regular occurrence in that region.

The increase in storm intensity during recent years has been tracked by the insurance industry, which has been hit hard by recent disasters. Until the mid 1980s, it was widely thought that windstorms or hurricanes with insured losses exceeding one billion (thousand million) US dollars were only possible, if at all, in the United States. But the gales that hit western Europe in October 1987 heralded a series of windstorm disasters which make losses of ten billion dollars seem commonplace. Hurricane Andrew, for instance, left in its wake insured losses estimated at nearly twenty-one billion dollars (1999 prices) with estimated total economic losses of nearly thirty-seven billion dollars. Figure 1.2 shows the costs of weather-related disasters[2] over the past fifty years as calculated by the insurance industry. It shows an increase in economic losses in such events by a factor of over 10 in real terms between the 1950s and the 1990s. Some of this increase can be attributed to the growth in population in particularly vulnerable areas and to other social or economic factors; the world community has undoubtedly become more vulnerable to disasters. However, a significant part of it has also arisen from the increased storminess in the late 1980s and 1990s compared with the 1950s.

Windstorms or hurricanes are by no means the only weather and climate extremes that cause disasters. Floods due to unusually intense or prolonged rainfall or droughts because of long periods of reduced rainfall (or its complete absence) can be even more devastating to human life and property. These events occur frequently in many parts of the world especially in the tropics and sub-tropics. There have been notable examples during the last two decades. Let me mention a few of the floods. In 1988, the highest flood levels ever recorded occurred in Bangladesh, eighty per cent of the entire country was affected; China experienced

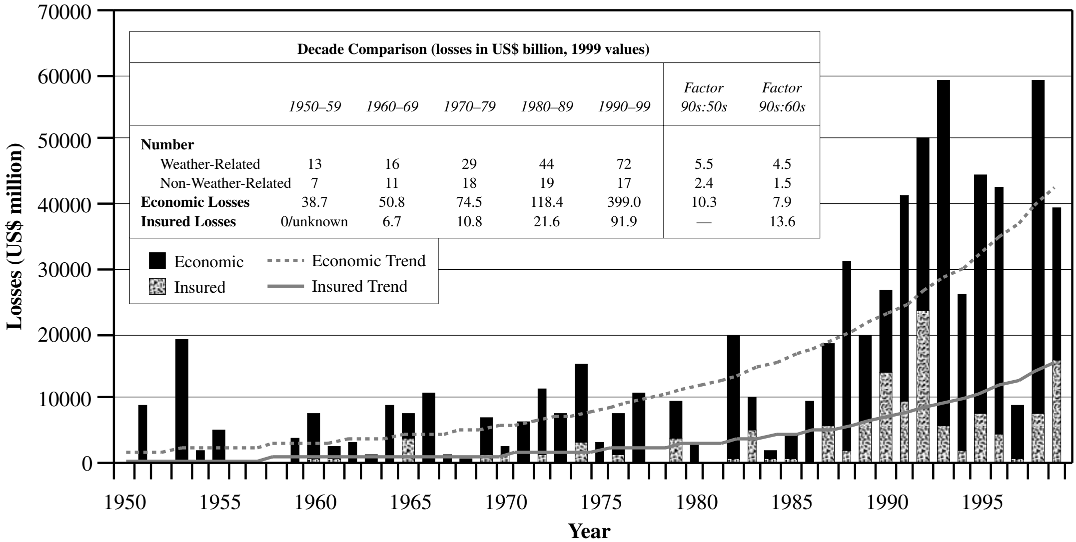


Figure 1.2 The total economic costs and the insured costs of catastrophic weather events for the second half of the twentieth century as recorded by the Munich Re insurance company. Both costs show a rapid upward trend in recent decades. The number of non-weather-related disasters is included for comparison. Tables 7.2 and 7.3 in Chapter 7 provide some regional detail and list some of the recent disasters with the greatest economic and insured losses.

devastating floods affecting many millions of people in 1991, 1994–5 and 1998; in 1993, flood waters rose to levels higher than ever recorded in the region of the Mississippi and Missouri rivers in the United States, flooding an area equivalent in size to one of the Great Lakes; major floods in Venezuela in 1999 led to a large landslide and left 30 000 people dead, and two widespread floods in Mozambique occurred within a year in 2000–1 leaving over half a million homeless. Droughts during these years have been particularly intense and prolonged in areas of Africa, both north and south. It is in Africa especially that they bear on the most vulnerable in the world, who have little resilience to major disasters. Figure 1.3 shows that in the 1980s droughts accounted for more deaths in Africa than all other disasters added together and illustrates the scale of the problem.

El Niño events

Rainfall patterns which lead to floods and droughts especially in tropical and semi-tropical areas are strongly influenced by the surface temperature of the oceans around the world, particularly the pattern of ocean surface temperature in the Pacific off the coast of South America

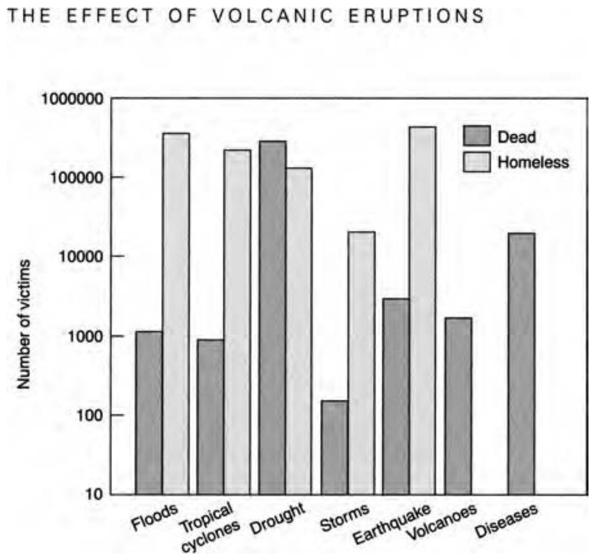


Figure 1.3 Recorded disasters in Africa, 1980–9, estimated by the Organization for African Unity.

(see Chapter 5 and Figure 5.9). About every three to five years a large area of warmer water appears and persists for a year or more. Because they usually occur around Christmas these are known as El Niño ('the boy child') events.[3] They have been well known for centuries to the countries along the coast of South America because of their devastating effect on the fishing industry; the warm top waters of the ocean prevent the nutrients from lower, colder levels required by the fish from reaching the surface.

A particularly intense El Niño, the second most intense in the twentieth century, occurred in 1982–3; the anomalous highs in ocean surface temperature compared to the average reached 7 °C. Droughts and floods somewhere in almost all the continents were associated with that El Niño (Figure 1.4). Like many events associated with weather and climate, El Niños often differ very much in their detailed character; that has been particularly the case with the El Niño events of the 1990s. For instance, the El Niño event that began in 1990 and reached maturity early in 1992, apart from some weakening in mid 1992, continued to be dominated by the warm phase until 1995. The exceptional floods in the central United States and in the Andes, and droughts in Australia and Africa are probably linked with this unusually protracted El Niño. This, the longest El Niño of the twentieth century, was followed in 1997–8 by the century's most intense El Niño that brought exceptional floods to China and to the Indian sub-continent and drought to Indonesia – that in turn brought extensive forest fires creating an exceptional blanket of thick smog that was experienced over a thousand miles away (Figure 1.1).

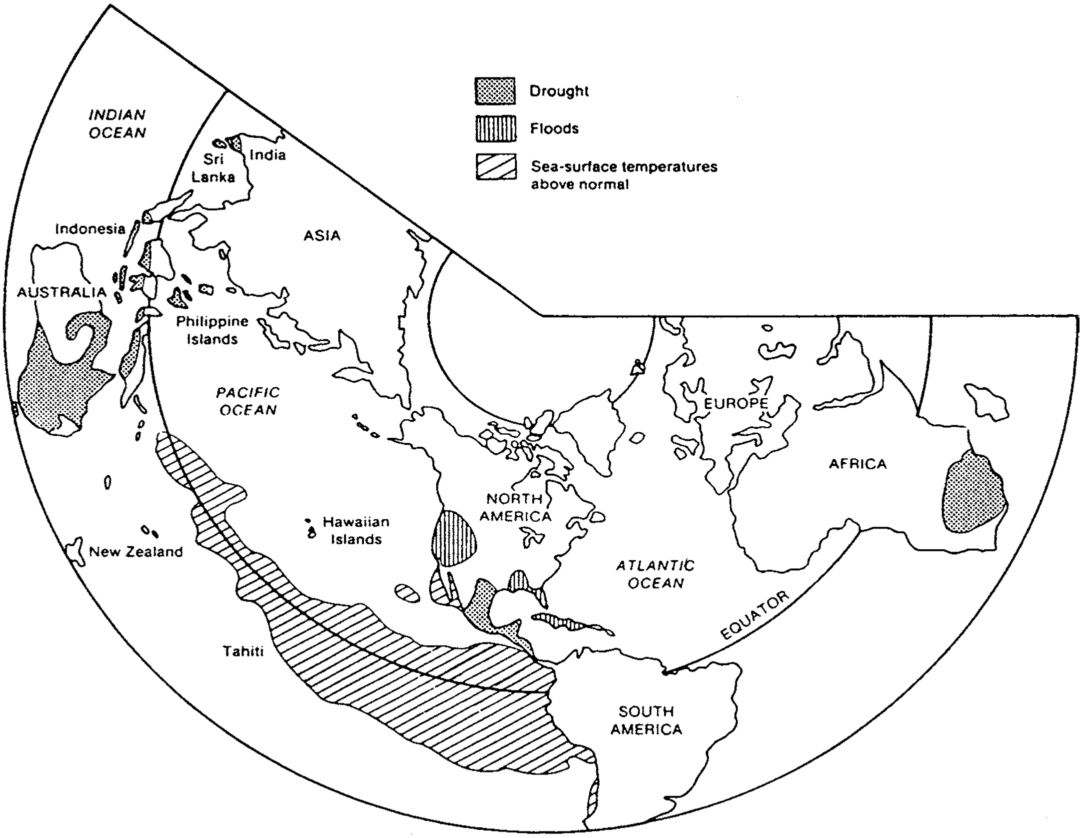


Figure 1.4 Regions where droughts and floods occurred associated with the 1982–3 El Niño.

Studies with computer models of the kind described later in Chapter 5 provide a scientific basis for links between the El Niño and these extreme weather events; they also give some confidence that useful forecasts of such disasters will in due course be possible. A scientific question that is being urgently addressed is the possible link between the character and intensity of El Niño events and global warming due to human-induced climate change.

The effect of volcanic eruptions on temperature extremes

Volcanoes inject enormous quantities of dust and gases into the upper atmosphere. Large amounts of sulphur dioxide are included, which through photochemical reactions using the Sun's energy are transformed to sulphuric acid and sulphate particles. Typically these particles remain in the stratosphere (the region of atmosphere above about 10 km in altitude) for several years before they fall into the lower atmosphere and are quickly washed out by rainfall. During this period they disperse around the whole globe and cut out some of the radiation from the Sun, thus tending to cool the lower atmosphere.

One of the largest volcanic eruptions in the twentieth century was that from Mount Pinatubo in the Philippines on 12 June 1991 which injected about twenty million tonnes of sulphur dioxide into the stratosphere together with enormous amounts of dust. This stratospheric dust caused spectacular sunsets around the world for many months following the eruption. The amount of radiation from the Sun reaching the lower atmosphere fell by about two per cent. Global average temperatures lower by about a quarter of a degree Celsius were experienced for the following two years. There is also evidence that some of the unusual weather patterns of 1991 and 1992, for instance unusually cold winters in the Middle East and mild winters in western Europe, were linked with effects of the volcanic dust.

Vulnerable to change

Over the centuries different human communities have adapted to their particular climate; any large change to the average climate tends to bring stress of one kind or another. It is particularly the extreme climate events and climate disasters which emphasise the importance of climate to our lives and which demonstrate to countries around the world their vulnerability to climate change – a vulnerability which is enhanced by rapidly increasing demands on resources.

But the question must be asked: how remarkable are these events? Do they point to a changing climate due to human activities? Do they provide evidence for global warming because of the increased carbon dioxide and other greenhouse gases being emitted into the atmosphere by burning fossil fuels?

Here a note of caution must be sounded. The range of normal natural climate variation is large. Climate extremes are nothing new. Climate records are continually being broken. In fact, a month without a broken record somewhere would itself be something of a record! Changes in climate that indicate a genuine long-term trend can only be identified after many years.

However, we know for sure that, because of human activities especially the burning of fossil fuels, carbon dioxide in the atmosphere has been increasing over the past two hundred years and more substantially over the past fifty years. To identify climate change related to this carbon dioxide increase, we need to look for trends in global warming over similar lengths of time. They are long compared with both the memories of a generation and the period for which accurate and detailed records exist. Although, therefore, it can be ascertained that there was more storminess, for instance, in the region of the north Atlantic during the 1980s and 1990s than in the previous three decades, it is difficult to know just how exceptional those decades were compared with other periods in previous centuries. There is even more difficulty in tracking detailed climate trends in many other parts of the world, owing to the lack of adequate records; further, trends in the frequency of rare events are not easy to detect.

The generally cold period worldwide during the 1960s and early 1970s caused speculation that the world was heading for an ice age. A British television programme about climate change called 'The ice age cometh' was prepared in the early 1970s and widely screened – but the cold trend soon came to an end. We must not be misled by our relatively short memories.

What is important is continually to make careful comparisons between practical observations of the climate and its changes and what scientific knowledge leads us to expect. During the last few years, as the occurrence of extreme events has made the public much more aware of environmental issues,[4] scientists in their turn have become more sure about just what human activities are doing to the climate. Later chapters will look in detail at the science of global warming and at the climate changes that we can expect, as well as investigating how these changes fit in with the recent climate record. Here, however, is a brief outline of our current scientific understanding.

The problem of global warming

Human activities of all kinds whether in industry, in the field (e.g. deforestation) or concerned with transport or the home are resulting in emissions of increasing quantities of gases, in particular the gas carbon dioxide, into the atmosphere. Every year these emissions currently add to the carbon already present in atmospheric carbon dioxide a further seven thousand million tonnes, much of which is likely to remain there for a period of a hundred years or more. Because carbon dioxide is a good absorber of heat radiation coming from the Earth's surface, increased carbon dioxide acts like a blanket over the surface, keeping it warmer than it would otherwise be. With the increased temperature the amount of water vapour in the atmosphere also increases, providing more blanketing and causing it to be even warmer.

Being kept warmer may sound appealing to those of us who live in cool climates. However, an increase in global temperature will lead to global climate change. If the change were small and occurred slowly enough we would almost certainly be able to adapt to it. However, with rapid expansion taking place in the world's industry the change is unlikely to be either small or slow. The estimate I present in later chapters is that, in the absence of efforts to curb the rise in the emissions of carbon dioxide, the global average temperature will rise by about a third of a degree Celsius every ten years – or about three degrees in a century.

This may not sound very much, especially when it is compared with normal temperature variations from day to night or between one day and the next. But it is not the temperature at one place but the temperature averaged over the whole globe. The predicted rate of change of three degrees a century is probably faster than the global average temperature has changed at any time over the past ten thousand years. And as there is a difference in global average temperature of only about five or six degrees between the coldest part of an ice age and the warm periods in between ice ages (see Figure 4.4), we can see that a few degrees in this global average can represent a big change in climate. It is to this change and especially to the very rapid rate of change that many ecosystems and human communities (especially those in developing countries) will find it difficult to adapt.

Not all the climate changes will in the end be adverse. While some parts of the world experience more frequent or more severe droughts, floods or significant sea level rise, in other places crop yields may increase due to the fertilising effect of carbon dioxide. Other places, perhaps for instance in the sub-arctic, may become more habitable. Even there, though, the likely rate of change will cause problems: large damage to buildings will occur in regions of melting permafrost, and trees in sub-arctic forests like trees elsewhere will need time to adapt to new climatic regimes.

Scientists are confident about the fact of global warming and climate change due to human activities. However, substantial uncertainty remains about just how large the warming will be and what will be the patterns of change in different parts of the world. Although some indications can be given, scientists cannot yet say in precise detail which regions will be most affected. Intensive research is needed to improve the confidence in scientific predictions.

Adaptation and mitigation

An integrated view of anthropogenic climate change is presented in Figure 1.5 where a complete cycle of cause and effect is shown. Begin in the lower right-hand corner where economic activity, both large and small scale, whether in developed or developing countries, results in emissions of greenhouse gases (of which carbon dioxide is the most

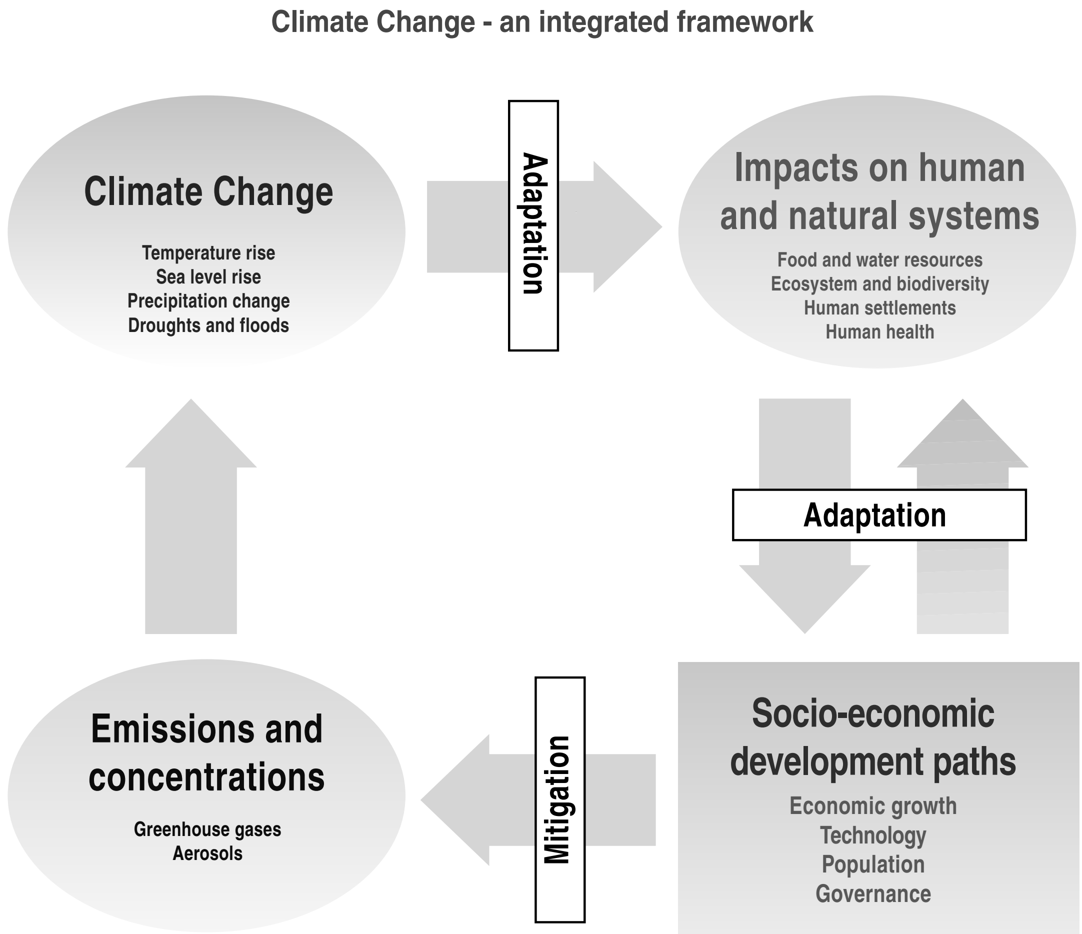


Figure 1.5 Climate change – an integrating framework; see text for explanation.

important) and aerosols. Moving in a clockwise direction around the diagram, these emissions lead to changes in atmospheric concentrations of important constituents that alter the energy input and output of the climate system and hence cause changes in the climate. These climate changes impact both humans and natural ecosystems altering patterns of resource availability and affecting human livelihood and health. These impacts in their turn affect human development in all its aspects. An anticlockwise arrow represents other effects of development on human communities and natural systems, for instance changes in land use that lead to deforestation and loss of biodiversity.

Figure 1.5 also shows how both causes and effects can be changed through *adaptation* and *mitigation*. In general adaptation is aimed at reducing the effects and mitigation is aimed at reducing the causes of climate change, in particular the emissions of the gases that give rise to it.

Uncertainty and response

Predictions of the future climate are surrounded with considerable uncertainty that arises from our imperfect knowledge both of the science of climate change and of the future scale of the human activities that are its cause. Politicians and others making decisions are therefore faced with the need to weigh all aspects of uncertainty against the desirability and the cost of the various actions that can be taken in response to the threat of climate change. Some mitigating action can be taken easily at relatively little cost (or even at a net saving of cost), for instance the development of programmes to conserve and save energy, and many schemes for reducing deforestation and encouraging the planting of trees. Other actions such as a large shift to energy sources that are free from significant carbon dioxide emissions (for example, renewable sources – biomass, hydro, wind, or solar energy) both in the developed and the developing countries of the world will take some time. Because however of the long timescales that are involved in the development of new energy infrastructure and in the response of the climate to emissions of gases like carbon dioxide, there is an urgency to begin these actions now. As we shall argue later (Chapter 9), to 'wait and see' is an irresponsible response.

In the following chapters I shall first explain the science of global warming, the evidence for it and the current state of the art regarding climate prediction. I shall then go on to say what is known about the likely impacts of climate change on human life – on water and food supplies for instance. The questions of why we should be concerned for the environment and what action should be taken in the face of scientific uncertainty are followed by consideration of the technical possibilities for large reductions in the emissions of carbon dioxide and how these might affect our energy sources and usage, including means of transport.

Finally I will address the issue of the 'global village'. So far as the environment is concerned, national boundaries are becoming less and less important; pollution in one country can now affect the whole world. Further, it is increasingly realised that problems of the environment are linked to other global problems such as population growth, poverty, the overuse of resources and global security. All these pose global challenges that must be met by global solutions.

Questions

1 Look through recent copies of newspapers and magazines for articles which mention climate change, global warming or the greenhouse effect. How many of the statements made are accurate?

2 Make up a simple questionnaire about climate change, global warming and the greenhouse effect to find out how much people know about these subjects, their relevance and importance. Analyse results from responses to the questionnaire in terms of the background of the respondents. Suggest ways in which people could be better informed.

Notes for Chapter 1

1 See Table 8.3 in Vellinga, P. V., Mills, E., Bowers, L., Berz, G., Huq, S., Kozak, L., Paultikof, J., Schanzenbacker, B., Shida, S., Soler, G., Benson, C., Bidan, P., Bruce, J., Huyck, P., Lemcke, G., Peara, A., Radevsky, R., van Schoubroeck, C., Dlugolecki, A. 2001. Insurance and other financial services. In McCarthy, J. J., Canziani, O., Leary, N. A., Dokken, D. J., White, K. S. (eds.) 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, Chapter 8.

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

3 A description of the variety of El Niño events and their impacts on different communities worldwide over centuries of human history can be found in a recent paperback by Ross Couiper-Johnston, *El Niño: the Weather Phenomena that Changed the World*. 2000. London: Hodder and Stoughton.

4 A gripping account of some of the changes over the last decades can be found in a recent book by Mark Lynas, *High Tides: News from a Warming World*. 2004. London: Flamingo.

Chapter 2
The greenhouse effect

The basic principle of global warming can be understood by considering the radiation energy from the Sun that warms the Earth's surface and the thermal radiation from the Earth and the atmosphere that is radiated out to space. On average these two radiation streams must balance. If the balance is disturbed (for instance by an increase in atmospheric carbon dioxide) it can be restored by an increase in the Earth's surface temperature.

How the Earth keeps warm

To explain the processes that warm the Earth and its atmosphere, I will begin with a very simplified Earth. Suppose we could, all of a sudden, remove from the atmosphere all the clouds, the water vapour, the carbon dioxide and all the other minor gases and the dust, leaving an atmosphere of nitrogen and oxygen only. Everything else remains the same. What, under these conditions, would happen to the atmospheric temperature?

The calculation is an easy one, involving a relatively simple radiation balance. Radiant energy from the Sun falls on a surface of one square metre in area outside the atmosphere and directly facing the Sun at a rate of about 1370 watts – about the power radiated by a reasonably sized domestic electric fire. However, few parts of the Earth's surface face the Sun directly and in any case for half the time they are pointing away from the Sun at night, so that the average energy falling on one square metre of a level surface outside the atmosphere is only one-quarter of this[1] or about 343 watts. As this radiation passes through the atmosphere a small

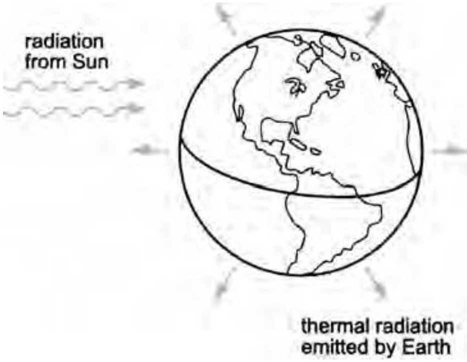


Figure 2.1 The radiation balance of planet Earth. The net incoming solar radiation is balanced by outgoing thermal radiation from the Earth.

amount, about six per cent, is scattered back to space by atmospheric molecules. About ten per cent on average is reflected back to space from the land and ocean surface. The remaining eighty-four per cent, or about 288 watts per square metre on average, remains actually to heat the surface – the power used by three good-sized incandescent electric light bulbs.

To balance this incoming energy, the Earth itself must radiate on average the same amount of energy back to space (Figure 2.1) in the form of thermal radiation. All objects emit this kind of radiation; if they are hot enough we can see the radiation they emit. The Sun at a temperature of about 6000 °C looks white; an electric fire at 800 °C looks red. Cooler objects emit radiation that cannot be seen by our eyes and which lies at wavelengths beyond the red end of the spectrum – infrared radiation (sometimes called long-wave radiation to distinguish it from the short-wave radiation from the Sun). On a clear, starry winter's night we are very aware of the cooling effect of this kind of radiation being emitted by the Earth's surface into space – it often leads to the formation of frost.

The amount of thermal radiation emitted by the Earth's surface depends on its temperature – the warmer it is, the more radiation is emitted. The amount of radiation also depends on how absorbing the surface is; the greater the absorption, the more the radiation. Most of the surfaces on the Earth, including ice and snow, would appear 'black' if we could see them at infrared wavelengths; that means that they absorb nearly all the thermal radiation which falls on them instead of reflecting it. It can be calculated[2] that, to balance the energy coming in, the average temperature of the Earth's surface must be –6 °C to radiate the right amount.[3] This is much colder than is actually the case. In fact, an average of temperatures measured near the surface all over the Earth – over the oceans as well as over the land – averaging, too, over the whole year, comes to about 15 °C. Some factor not yet taken into account is needed to explain this discrepancy.

Table 2.1 *The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2001*

Gas	Mixing ratio or mole fraction[a] expressed as fraction* or parts per million (ppm)
Nitrogen (N_2)	0.78*
Oxygen (O_2)	0.21*
Water vapour (H_2O)	Variable (0–0.02*)
Carbon dioxide (CO_2)	370
Methane (CH_4)	1.8
Nitrous oxide (N_2O)	0.3
Chlorofluorocarbons	0.001
Ozone (O_3)	Variable (0–1000)

[a] For definition see Glossary.

The greenhouse effect

The gases nitrogen and oxygen that make up the bulk of the atmosphere (Table 2.1 gives details of the atmosphere's composition) neither absorb nor emit thermal radiation. It is the water vapour, carbon dioxide and some other minor gases present in the atmosphere in much smaller quantities (Table 2.1) that absorb some of the thermal radiation leaving the surface, acting as a partial blanket for this radiation and causing the difference of 21 °C or so between the actual average surface temperature on the Earth of about 15 °C and the figure of −6 °C which applies when the atmosphere contains nitrogen and oxygen only.[4] This blanketing is known as the *natural greenhouse effect* and the gases are known as greenhouse gases. It is called 'natural' because all the atmospheric gases (apart from the chlorofluorocarbons – CFCs) were there long before human beings came on the scene. Later on I will mention the *enhanced greenhouse effect*: the added effect caused by the gases present in the atmosphere due to human activities such as the burning of fossil fuels and deforestation.

The basic science of the greenhouse effect has been known since early in the nineteenth century (see box) when the similarity between the radiative properties of the Earth's atmosphere and of the glass in a greenhouse (Figure 2.2) was first pointed out – hence the name 'greenhouse effect'. In a greenhouse, visible radiation from the Sun passes almost

Pioneers of the science of the greenhouse effect[5]

The warming effect of the greenhouse gases in the atmosphere was first recognised in 1827 by the French scientist Jean-Baptiste Fourier, best known for his contributions to mathematics. He also pointed out the similarity between what happens in the atmosphere and in the glass of a greenhouse, which led to the name 'greenhouse effect'. The next step was taken by a British scientist, John Tyndall, who, around 1860, measured the absorption of infrared radiation by carbon dioxide and water vapour; he also suggested that a cause of the Ice Ages might be a decrease in the greenhouse effect of carbon dioxide. It was a Swedish chemist, Svante Arrhenius, in 1896, who calculated the effect of an increasing concentration of greenhouse gases; he estimated that doubling the concentration of carbon dioxide would increase the global average temperature by 5 °C to 6 °C, an estimate not too far from our present understanding.[6] Nearly fifty years later, around 1940, G. S. Callendar, working in England, was the first to calculate the warming due to the increasing carbon dioxide from the burning of fossil fuels.

The first expression of concern about the climate change which might be brought about by increasing greenhouse gases was in 1957, when Roger Revelle and Hans Suess of the Scripps Institute of Oceanography in California published a paper which pointed out that in the build-up of carbon dioxide in the atmosphere, human beings are carrying out a large-scale geophysical experiment. In the same year, routine measurements of carbon dioxide were started from the observatory on Mauna Kea in Hawaii. The rapidly increasing use of fossil fuels since then, together with growing interest in the environment, has led to the topic of global warming moving up the political agenda through the 1980s, and eventually to the Climate Convention signed in 1992 – of which more in later chapters.

unimpeded through the glass and is absorbed by the plants and the soil inside. The thermal radiation that is emitted by the plants and soil is, however, absorbed by the glass that re-emits some of it back into the greenhouse. The glass thus acts as a 'radiation blanket' helping to keep the greenhouse warm.

However, the transfer of radiation is only one of the ways heat is moved around in a greenhouse. A more important means of heat transfer is due to convection, in which less dense warm air moves upwards and more dense cold air moves downwards. A familiar example of this process is the use of convective electric heaters in the home, which heat a room by stimulating convection in it. The situation in the greenhouse

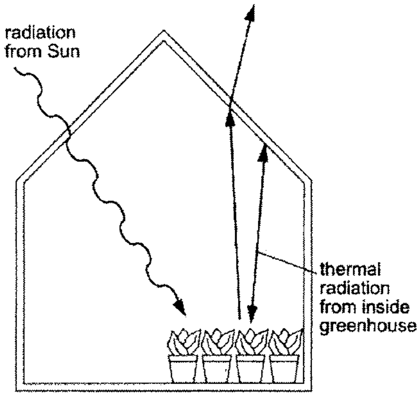


Figure 2.2 A greenhouse has a similar effect to the atmosphere on the incoming solar radiation and the emitted thermal radiation.

is therefore more complicated than would be the case if radiation were the only process of heat transfer.

Mixing and convection are also present in the atmosphere, although on a much larger scale, and in order to achieve a proper understanding of the greenhouse effect, convective heat transfer processes in the atmosphere must be taken into account as well as radiative ones.

Within the atmosphere itself (at least in the lowest three-quarters or so of the atmosphere up to a height of about 10 km which is called the troposphere) convection is, in fact, the dominant process for transferring heat. It acts as follows. The surface of the Earth is warmed by the sunlight it absorbs. Air close to the surface is heated and rises because of its lower density. As the air rises it expands and cools – just as the air cools as it comes out of the valve of a tyre. As some air masses rise, other air masses descend, so the air is continually turning over as different movements balance each other out – a situation of convective equilibrium. Temperature in the troposphere falls with height at a rate determined by these convective processes; the fall with height (called the lapse-rate) turns out on average to be about 6 °C per kilometre of height (Figure 2.3).

A picture of the transfer of radiation in the atmosphere may be obtained by looking at the thermal radiation emitted by the Earth and its atmosphere as observed from instruments on satellites orbiting the Earth (Figure 2.4). At some wavelengths in the infrared the atmosphere – in the absence of clouds – is largely transparent, just as it is in the visible part of the spectrum. If our eyes were sensitive at these wavelengths we would be able to peer through the atmosphere to the Sun, stars and Moon above, just as we can in the visible spectrum. At these wavelengths all the radiation originating from the Earth's surface leaves the atmosphere.

At other wavelengths radiation from the surface is strongly absorbed by some of the gases present in the atmosphere, in particular by water vapour and carbon dioxide.

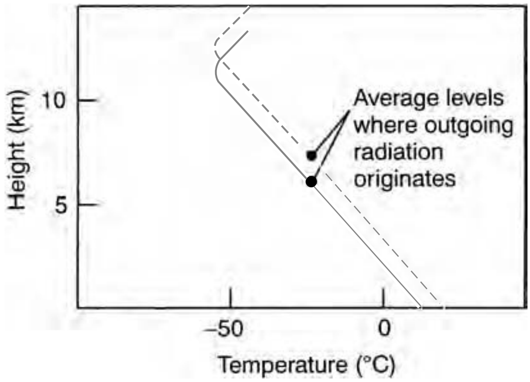


Figure 2.3 The distribution of temperature in a convective atmosphere (full line). The broken line shows how the temperature increases when the amount of carbon dioxide present in the atmosphere is increased (in the diagram the difference between the lines is exaggerated – for instance, for doubled carbon dioxide in the absence of other effects the increase in temperature is about 1.2 °C). Also shown for the two cases are the average levels from which thermal radiation leaving the atmosphere originates (about 6 km for the unperturbed atmosphere).

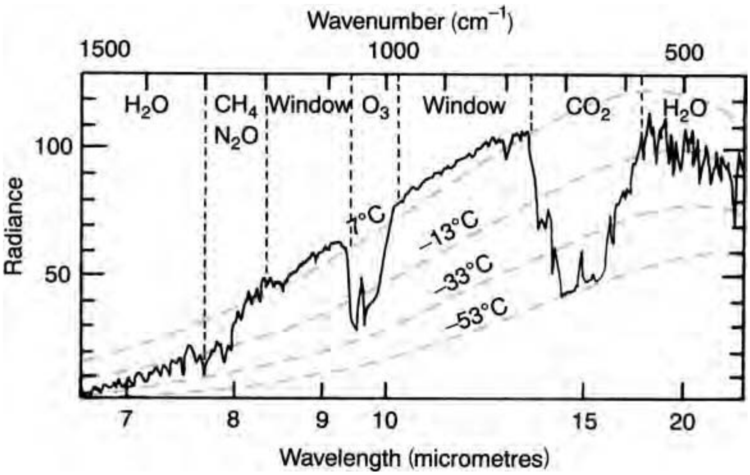
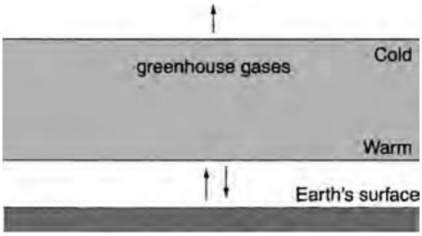


Figure 2.4 Thermal radiation in the infrared region (the visible part of the spectrum is between about 0.4 and 0.7 μm) emitted from the Earth's surface and atmosphere as observed over the Mediterranean Sea from a satellite instrument orbiting above the atmosphere, showing parts of the spectrum where different gases contribute to the radiation. Between the wavelengths of about 8 and 14 μm, apart from the ozone band, the atmosphere, in the absence of clouds, is substantially transparent; this is part of the spectrum called a 'window' region. Superimposed on the spectrum are curves of radiation from a black body at 7 °C, −13 °C, −33 °C and −53 °C. The units of radiance are watts per square metre per steradian per wavenumber.

Figure 2.5 The blanketing effect of greenhouse gases.



Objects that are good absorbers of radiation are also good emitters of it. A black surface is both a good absorber and a good emitter, while a highly reflecting surface absorbs rather little and emits rather little too (which is why highly reflecting foil is used to cover the surface of a vacuum flask and why it is placed above the insulation in the lofts of houses).

Absorbing gases in the atmosphere absorb some of the radiation emitted by the Earth's surface and in turn emit radiation out to space. The amount of thermal radiation they emit is dependent on their temperature.

Radiation is emitted out to space by these gases from levels somewhere near the top of the atmosphere – typically from between 5 and 10 km high (see Figure 2.3). Here, because of the convection processes mentioned earlier, the temperature is much colder – 30 to 50 °C or so colder – than at the surface. Because the gases are cold, they emit correspondingly less radiation. What these gases have to do, therefore, is absorb some of the radiation emitted by the Earth's surface but then to emit much less radiation out to space. They, therefore, act as a radiation blanket over the surface (note that the outer surface of a blanket is colder than inside the blanket) and help to keep it warmer than it would otherwise be[7] (Figure 2.5).

There needs to be a balance between the radiation coming in and the radiation leaving the top of the atmosphere – as there was in the very simple model with which this chapter started. Figure 2.6 shows the various components of the radiation entering and leaving the top of the atmosphere for the real atmosphere situation. On average, 240 watts per square metre of solar radiation are absorbed by the atmosphere and the surface; this is less than the 288 watts mentioned at the beginning of the chapter, because now the effect of clouds is being taken into account. Clouds reflect some of the incident radiation from the Sun back out to space. However, they also absorb and emit thermal radiation and have a blanketing effect similar to that of the greenhouse gases. These two effects work in opposite senses: one (the reflection of solar radiation) tends to cool the Earth's surface and the other (the absorption of thermal radiation) tends to warm it. Careful consideration of these two effects shows that on average the net effect of clouds on the total budget of radiation results in a slight cooling of the Earth's surface.[8]

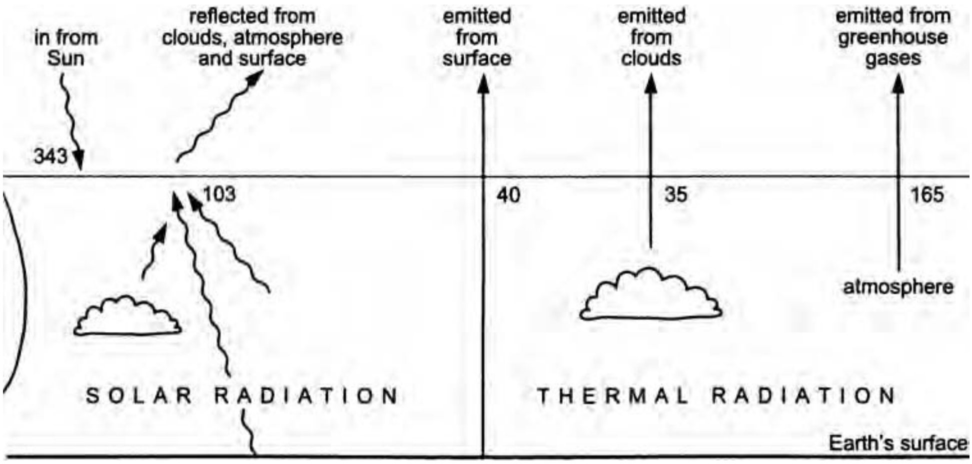


Figure 2.6 Components of the radiation (in watts per square metre) which on average enter and leave the Earth's atmosphere and make up the radiation budget for the atmosphere.

The numbers in Figure 2.6 demonstrate the required balance – 240 watts per square metre on average coming in and 240 watts per square metre on average going out. The temperature of the surface and hence of the atmosphere above adjusts itself to ensure that this balance is maintained. It is interesting to note that the greenhouse effect can only operate if there are colder temperatures in the higher atmosphere. Without the structure of decreasing temperature with height, therefore, there would be no greenhouse effect on the Earth.

Mars and Venus

Similar greenhouse effects also occur on our nearest planetary neighbours, Mars and Venus. Mars is smaller than the Earth and possesses, by Earth's standards, a very thin atmosphere. A barometer on the surface of Mars would record an atmospheric pressure less than one per cent of that on the Earth. Its atmosphere, which consists almost entirely of carbon dioxide, contributes a small but significant greenhouse effect.

The planet Venus, which can often be seen fairly close to the Sun in the morning or evening sky, has a very different atmosphere to Mars. Venus is about the same size as the Earth. A barometer for use on Venus would need to survive very hostile conditions and would need to be able to measure a pressure about one hundred times as great as that on the Earth. Within the Venus atmosphere, which consists very largely of carbon dioxide, deep clouds consisting of droplets of almost pure sulphuric acid completely cover the planet and prevent most of the sunlight from reaching the surface. Some Russian space probes that have landed there have recorded what would be dusk-like conditions on the Earth – only one or two per cent of the sunlight present above the clouds penetrates that far. One might suppose, because of the small amount of solar energy available to keep the surface warm, that it would be rather cool; on the contrary, measurements from the same Russian space probes find a temperature there of about 525 °C – a dull red heat, in fact.

The reason for this very high temperature is the greenhouse effect. Because of the very thick absorbing atmosphere of carbon dioxide, little of the thermal radiation from the surface can get out. The atmosphere acts as such an effective radiation blanket that, although there is not much solar energy to warm the surface, the greenhouse effect amounts to nearly 500 °C.

The 'runaway' greenhouse effect

What occurs on Venus is an example of what has been called the 'runaway' greenhouse effect. It can be explained by imagining the early history of the Venus atmosphere, which was formed by the release of gases from the interior of the planet. To start with it would contain a lot of water vapour, a powerful greenhouse gas (Figure 2.7). The greenhouse effect of the water vapour would cause the temperature at the surface to rise. The increased temperature would lead to more evaporation of water from the surface, giving more atmospheric water vapour, a larger greenhouse effect and therefore a further increased surface temperature. The process would continue until either the atmosphere became saturated with water vapour or all the available water had evaporated.

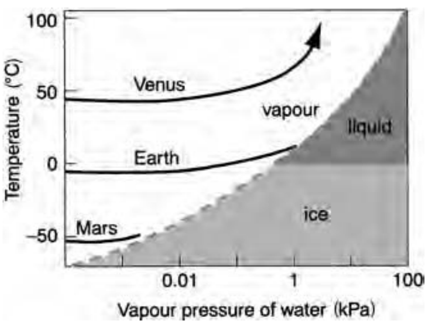


Figure 2.7 Illustrating the evolution of the atmospheres of the Earth, Mars and Venus. In this diagram, the surface temperatures of the three planets are plotted against the vapour pressure of water in their atmospheres as they evolved. Also on the diagram (dashed) are the phase lines for water, dividing the diagram into regions where vapour, liquid water or ice are in equilibrium. For Mars and the Earth the greenhouse effect is halted when water vapour is in equilibrium with ice or liquid water. For Venus no such halting occurs and the diagram illustrates the 'runaway' greenhouse effect.

A runaway sequence something like this seems to have occurred on Venus. Why, we may ask, has it not happened on the Earth, a planet of about the same size as Venus and, so far as is known, of a similar initial chemical composition? The reason is that Venus is closer to the Sun than the Earth; the amount of solar energy per square metre falling on Venus is about twice that falling on the Earth. The surface of Venus, when there was no atmosphere, would have started off at a temperature of just over 50 °C (Figure 2.7). Throughout the sequence described above for Venus, water on the surface would have been continuously boiling. Because of the high temperature, the atmosphere would never have become saturated with water vapour. The Earth, however, would have started at a colder temperature; at each stage of the sequence it would have arrived at an equilibrium between the surface and an atmosphere saturated with water vapour. There is no possibility of such runaway greenhouse conditions occurring on the Earth.

The enhanced greenhouse effect

After our excursion to Mars and Venus, let us return to Earth! The natural greenhouse effect is due to the gases water vapour and carbon dioxide present in the atmosphere in their natural abundances as now on Earth. The amount of water vapour in our atmosphere depends mostly on the temperature of the surface of the oceans; most of it originates through evaporation from the ocean surface and is not influenced directly by human activity. Carbon dioxide is different. Its amount has changed substantially – by about thirty per cent so far – since the Industrial Revolution, due to human industry and also because of the removal of forests (see Chapter 3). Future projections are that, in the absence of controlling factors, the rate of increase in atmospheric carbon dioxide will accelerate and that its atmospheric concentration will double from its pre-industrial value within the next hundred years (Figure 6.2).

This increased amount of carbon dioxide is leading to global warming of the Earth's surface because of its enhanced greenhouse effect. Let us imagine, for instance, that the amount of carbon dioxide in the atmosphere suddenly doubled, everything else remaining the same (Figure 2.8). What would happen to the numbers in the radiation budget presented earlier (Figure 2.6)? The solar radiation budget would not be affected. The greater amount of carbon dioxide in the atmosphere means that the thermal radiation emitted from it will originate on average from a higher and colder level than before (Figure 2.3). The thermal radiation budget will therefore be reduced, the amount of reduction being about 4 watts per square metre (a more precise value is 3.7).[9]

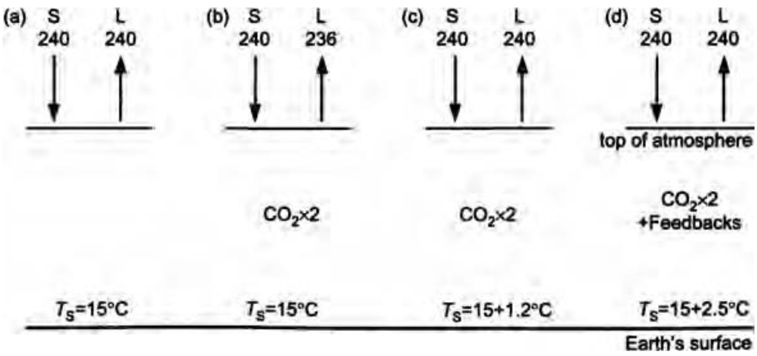


Figure 2.8 Illustrating the enhanced greenhouse gas effect. Under natural conditions (a) the net solar radiation coming in (S = 240 watts per square metre) is balanced by thermal radiation (L) leaving the top of the atmosphere; average surface temperature (T_S) is 15 °C. If the carbon dioxide concentration is suddenly doubled (b), L is decreased by 4 watts per square metre. Balance is restored if nothing else changes (c) apart from the temperature of the surface and lower atmosphere, which rises by 1.2 °C. If feedbacks are also taken into account (d), the average temperature of the surface rises by about 2.5 °C.

This causes a net imbalance in the overall budget of 4 watts per square metre. More energy is coming in than going out. To restore the balance the surface and lower atmosphere will warm up. If nothing changes apart from the temperature – in other words, the clouds, the water vapour, the ice and snow cover and so on are all the same as before – the temperature change turns out to be about 1.2 °C.

In reality, of course, many of these other factors will change, some of them in ways that add to the warming (these are called positive feedbacks), others in ways that might reduce the warming (negative feedbacks). The situation is therefore much more complicated than this simple calculation. These complications will be considered in more detail in Chapter 5. Suffice it to say here that the best estimate at the present time of the increased average temperature of the Earth's surface if carbon dioxide levels were to be doubled is about twice that of the simple calculation: 2.5 °C. As the last chapter explained, for the global average temperature this is a large change. It is this global warming expected to result from the enhanced greenhouse effect that is the cause of current concern.

Having dealt with a doubling of the amount of carbon dioxide, it is interesting to ask what would happen if all the carbon dioxide were removed from the atmosphere. It is sometimes supposed that the outgoing radiation would be changed by 4 watts per square metre in the other direction and that the Earth would then cool by one or two degrees Celsius. In fact, that would happen if the carbon dioxide amount were to be halved. If it were to be removed altogether, the change in outgoing radiation would be around 25 watts per square metre – six times as big – and the temperature change would be similarly increased. The reason for this is that with the amount of carbon dioxide currently present in the atmosphere there is maximum carbon dioxide absorption over much of the region of the spectrum where it absorbs (Figure 2.4), so that a big change in gas concentration leads to a relatively small change in the amount of radiation it absorbs.[10] This is like the situation in a pool of water: when it is clear, a small amount of mud will make it appear muddy, but when it is muddy, adding more mud only makes a small difference.

An obvious question to ask is: has evidence of the enhanced greenhouse effect been seen in the recent climatic record? Chapter 4 will look at the record of temperature on the Earth during the last century or so, during which the Earth has warmed on average by rather more than half a degree Celsius. We shall see in Chapters 4 and 5 that there are good reasons for attributing most of this warming to the enhanced greenhouse effect, although because of the size of natural climate variability the exact amount of that attribution remains subject to some uncertainty.

To summarise the argument so far:

- No one doubts the reality of the natural greenhouse effect, which keeps us over 20 °C warmer than we would otherwise be. The science of it is well understood; it is similar science that applies to the enhanced greenhouse effect.
- Substantial greenhouse effects occur on our nearest planetary neighbours, Mars and Venus. Given the conditions that exist on those planets, the sizes of their greenhouse effects can be calculated, and good agreement has been found with those measurements which are available.
- Study of climates of the past gives some clues about the greenhouse effect, as Chapter 4 will show.

First, however, the greenhouse gases themselves must be considered. How does carbon dioxide get into the atmosphere, and what other gases affect global warming?

Questions

1 Carry out the calculation described in Note 4 (refer also to Note 2) which obtains an equilibrium average temperature of −18 °C for an Earth partially covered with clouds such that thirty per cent of the incoming solar radiation is reflected. If clouds are assumed to cover half the Earth and if the reflectivity of the clouds increases by one per cent what change will this make in the resulting equilibrium average temperature?

2 It is sometimes argued that the greenhouse effect of carbon dioxide is negligible because its absorption band in the infrared is so close to saturation that there is very little additional absorption of radiation emitted from the surface. What are the fallacies in this argument?
3 Use the information in Figure 2.4 to estimate approximately the surface temperature that would result if carbon dioxide were completely removed from the atmosphere. What is required is that the total energy radiated by the Earth plus atmosphere should remain the same, i.e. the area under the radiance curve in Figure 2.4 should be unaltered. On this basis construct a new curve with the carbon dioxide band absent.[11]
4 Using information from books or articles on climatology or meteorology describe why the presence of water vapour in the atmosphere is of such importance in determining the atmosphere's circulation.
5 Estimates of regional warming due to increased greenhouse gases are generally larger over land areas than over ocean areas. What might be the reasons for this?
6 (For students with a background in physics) What is meant by Local Thermodynamic Equilibrium (LTE),[12] a basic assumption underlying calculations of radiative transfer in the lower atmosphere appropriate to discussions of the greenhouse effect? Under what conditions does LTE apply?

Notes for Chapter 2

1 It is about one-quarter because the area of the Earth's surface is four times the area of the disc, which is the projection of the Earth facing the Sun; see Figure 2.1.
2 The radiation by a black body is the Stefan–Boltzmann constant (5.67×10^{-8} J m^{-2} K^{-4} s^{-1}) multiplied by the fourth power of the body's absolute temperature in Kelvin. The absolute temperature is the temperature in degrees Celsius plus 273 (1 K = 1 °C).
3 These calculations using a simple model of an atmosphere containing nitrogen and oxygen only have been carried out to illustrate the effect of the other gases, especially water vapour and carbon dioxide. It is not, of course, a model that can exist in reality. All the water vapour could not be removed from the atmosphere above a water or ice surface. Further, with an average surface temperature of −6 °C, in a real situation the surface would have much more ice cover. The additional ice would reflect more solar energy out to space leading to a further lowering of the surface temperature.
4 The above calculation is often carried out using a figure of thirty per cent for the average reflectivity of the Earth and atmosphere, rather than the sixteen per cent assumed here; the calculation of surface temperature then gives −18 °C for the average surface temperature rather than the −6 °C found here. The higher figure of thirty per cent for the Earth's average reflectivity is applicable when clouds are also included, in which case the average temperature of −18 °C is not applicable to the Earth's surface but to some appropriate level in the atmosphere. Further, clouds not only reflect

solar radiation but also absorb thermal radiation, and so have a blanketing effect similar to greenhouse gases. For the purposes of illustrating the effect of greenhouse gases, therefore, it is more correct to omit the effect of clouds from this initial calculation.

5 Further details can be found in Mudge, F. B. The development of greenhouse theory of global climate change from Victorian times. 1997. *Weather*, **52**, pp. 13–16.

6 A range of 1.5 to 4.5 °C is quoted in Chapter 6, page 120.

7 The formal theory of the greenhouse effect is presented in Houghton, J. T. 2002. *The Physics of Atmospheres*, third edition, Chapter 2. Cambridge: Cambridge University Press. See also Chapter 14 of that book.

8 More detail of the radiative effects of clouds is given in Chapter 5; see Figures 5.14 and 5.15.

9 More detailed information about the enhanced greenhouse effect can be found in Houghton, J. T. 2002. *The Physics of Atmospheres*, third edition, Chapter 14. Cambridge: Cambridge University Press.

10 The dependence of the absorption on the concentration of gas is approximately logarithmic.

11 For some helpful diagrams and more information about the infrared spectrum of different greenhouse gases, see Harries, J. E. 1996. The greenhouse Earth: a view from space. *Quarterly Journal of the Royal Meteorological Society*, **122**, pp. 799–818.

12 For information about LTE see, for instance, Houghton, J. T. 2002. *The Physics of Atmospheres*, third edition. Cambridge: Cambridge University Press.

Chapter 3
The greenhouse gases

The greenhouse gases are those gases in the atmosphere which, by absorbing thermal radiation emitted by the Earth's surface, have a blanketing effect upon it. The most important of the greenhouse gases is water vapour, but its amount in the atmosphere is not changing directly because of human activities. The important greenhouse gases that are directly influenced by human activities are carbon dioxide, methane, nitrous oxide, the chlorofluorocarbons (CFCs) and ozone. This chapter will describe what is known about the origin of these gases, how their concentration in the atmosphere is changing and how it is controlled. Also considered will be particles in the atmosphere of anthropogenic origin that can act to cool the surface.

Which are the most important greenhouse gases?

Figure 2.4 illustrated the regions of the infrared spectrum where the greenhouse gases absorb. Their importance as greenhouse gases depends both on their concentration in the atmosphere (Table 2.1) and on the strength of their absorption of infrared radiation. Both these quantities differ greatly for various gases.

Carbon dioxide is the most important of the greenhouse gases that are increasing in atmospheric concentration because of human activities. If, for the moment, we ignore the effects of the CFCs and of changes in ozone, which vary considerably over the globe and which are therefore more difficult to quantify, the increase in carbon dioxide (CO_2) has contributed about seventy per cent of the enhanced greenhouse effect