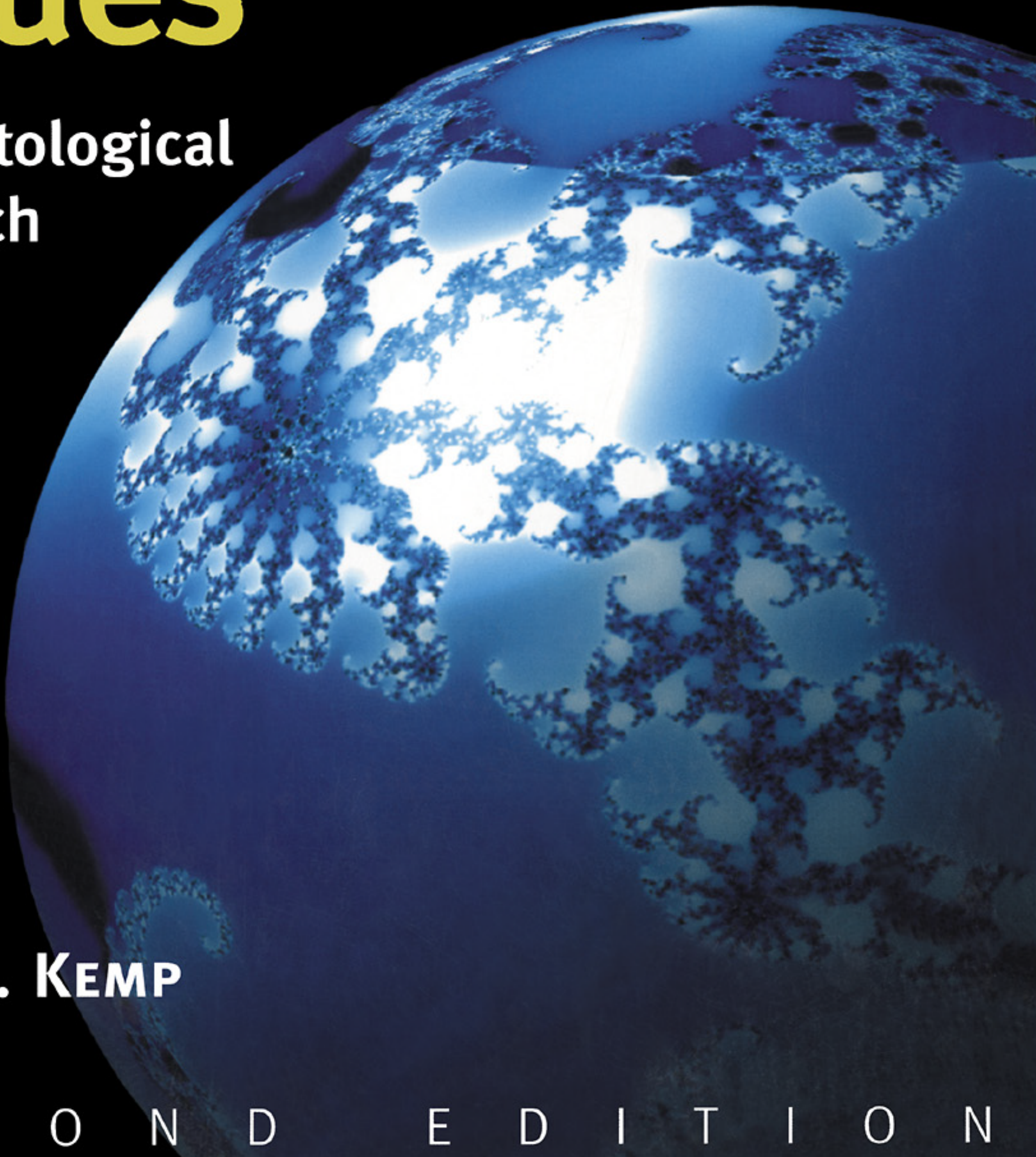
# Global Environmental Issues

## A Climatological Approach



DAVID D. KEMP

SECOND EDITION

# Global environmental issues

This book provides a balanced account of the global environmental issues which threaten our society and which we neglect at our peril. Analysing both societal and environmental components of the issues—global warming, ozone depletion, acid rain and drought—the book offers a valuable integrative approach. At a time when the technical level of publications on environmental issues is rising, this introductory text expresses sophisticated scientific ideas in a clear, non-technical manner.

Emphasising the climatological dimension common to all environmental issues, *Global Environmental Issues* recognises the multi-faceted nature of the issues, their common causes and the possibility of common solutions. Assessment of socio-economic, cultural and political factors provides a balanced introduction to both the dangers and advantages of human interference with the environment. What have we done to deserve our current environmental crisis? Can we solve our current environmental problems, or is it too late?

This new edition of a best-selling text is completely updated and expanded to include greater detail and new material such as a new section on atmospheric modelling. A glossary has been added together with a bibliography for further reading at the end of each chapter, allowing readers to develop their interest in specific topics. This interdisciplinary text will prove invaluable to students in geography, environmental studies and other courses in which the environmental approach is emphasised.

**David D.Kemp** is Professor of Geography at Lakehead University, Canada and has over twenty-five years of experience in teaching climatology and environmental studies.

To Susan, Heather, Qais, Qarma, Beisan, Alisdair, Colin, Mairi, Eilidh, Euan, Deirdre, Neil, Ross, Andrew, Heather Lynn and all of their generation whose future requires that we find solutions to our current environmental problems.

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DAVID D.KEMP

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# Contents

# Figures

# Tables

# Preface

The study of global environmental issues is very much a growth industry at the present time, and the amount of new material which has appeared since this book was first published in 1990 is little short of phenomenal. As the study of the issues has intensified, the technical level of the associated scientific reports has tended to increase also. To accommodate this, the text in the present volume has been expanded and updated to include greater detail on the topics covered, and the number of tables and figures has been increased by almost 70 per cent. It remains an introductory text, however, multidisciplinary in its content, and designed for students in geography and environmental studies programmes, but also appropriate for courses in other disciplines where the environmental approach is followed. To retain the broad readership that this implies, a glossary has been added to this edition, providing succinct definitions of the broad range of terms used in the book for those who require additional information beyond that readily available in the text. The inclusion of a brief bibliography for further reading at the end of each chapter serves a similar function, but also allows readers to develop their interests in specific topics. For those interested and able to pursue the topics to a more advanced level, the main bibliography includes the appropriate scientific and academic references.

The topics covered in the second edition remain the same as in the first, but with some important changes in emphasis. With the end of the 'Cold War' and the disintegration of the Soviet Union, nuclear war has ceased to be a pressing concern. As a result, nuclear winter is now considered to be irrelevant by many researchers, and has received little attention in recent years. It is therefore no longer considered in a separate chapter, but has been condensed into the chapter on atmospheric turbidity, where it logically belongs since the predicted onset of nuclear winter is initiated by a rapid increase in turbidity.

Among the other issues, ozone depletion and global warming have emerged as the topics eliciting the greatest level of concern in recent years. As a result there is a large volume of new material in these issues, and that is reflected in the changes made in the chapters that deal with them.

Much of the recent work on environmental issues has involved the use of computerized atmospheric circulation models. In recognition of this, a new section outlining the development and characteristics of such models has been added to the chapter on the atmosphere. The bulk of the chapter continues to provide background on the various atmospheric elements involved in the creation and intensification of current environmental problems, and references a number of well-established introductory climatology texts which should be consulted by students who require to develop, renew or broaden their experience in atmospheric studies.

An encouraging development since the publication of the first edition of this book has been the (somewhat) slow, but steady progress from investigation to decision-making. Control or abatement programmes have been introduced to deal with the problems of acid rain, atmospheric turbidity and ozone depletion, and are at the discussion stage for global warming. Successful implementation of these programmes will require the cooperation of all levels of society, and community support is most likely to come from a public well-informed about the nature and extent of the problems. This book will, I hope, contribute towards that end by providing a balanced and readable account of the global environmental issues which threaten our society, and which we neglect at our peril.

**David D.Kemp**
**Thunder Bay**

# Acknowledgements

The preparation of the original edition of this book involved the work of many people. Although the experience gained then made things easier for me this time, this second edition—like the first—represents the combined efforts of a variety of individuals who helped me in many ways. Tristan Palmer of Routledge was the ideal editor, providing appropriate guidance and encouragement as required. In the Department of Geography at Lakehead, Gwen Henry dealt with the revisions and additions in her usual efficient manner, and Cathy Chapin redrew many of the maps and diagrams for this edition. Catherine Fear provided invaluable editorial services and Jane Mayger guided me through the production process. Their help is much appreciated. The reviewers who commented on the first edition, and my colleagues and students who drew my attention to new material have my thanks also. I am again grateful to my wife and daughters for their patience, encouragement and understanding while living under the shadow of 'the book'. My thanks are also due to the following for allowing me to reproduce copyright material:

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# Acronyms

| | |
|---|---|
| **AGGG** | Advisory Group on Greenhouse Gases |
| **AOSIS** | Alliance of Small Islands States |
| **CEGB** | Central Electricity Generating Board |
| **CFC** | Chlorofluorocarbon |
| **CIAP** | Climatic Impact Assessment Program |
| **cT** | Continental tropical (air) |
| **DMS** | Dimethyl sulphide |
| **DVI** | Dust veil index |
| **EASOE** | European Arctic Stratospheric Ozone Experiment |
| **ENSO** | El Niño/Southern Oscillation |
| **ENUWAR** | Environmental consequences of nuclear war |
| **EPA** | Environmental Protection Agency (USA) |
| **FBC** | Fluidized bed combustion |
| **FGD** | Flue gas desulphurization |
| **GVI** | Glaciological volcanic index |
| **HCFC** | Hydrochlorofluorocarbon |
| **ICSU** | International Council of Scientific Unions |
| **IIASA** | International Institute for Applied Systems Analysis |
| **INCO** | International Nickle Company |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ITCZ** | Intertropical Convergence Zone |
| **LIMB** | Lime injection multi-stage burning |
| **LRTAP** | Long range transportation of atmospheric pollution |
| **MSA** | Methane sulphonic acid |
| **mT** | Maritime tropical (air) |
| **NAWAPA** | North American Water and Power Alliance |
| **NCGCC** | National Coordinating Group on Climate Change (China) |
| **NGO** | Nongovernmental organization |
| **OECD** | Organization for Economic Cooperation and Development |
| **OPEC** | Organization of Petroleum Exporting Countries |
| **ppbv** | parts per billion by volume |
| **ppmv** | parts per million by volume |
| **pptv** | parts per trillion by volume |
| **SCEP** | Study of Critical Environmental Problems |
| **SCOPE** | Scientific Committee on Problems of the Environment |
| **SCR** | Selective catalytic reduction |
| **SMD** | Soil moisture deficit |

**SMIC** Study of Man's Impact on Climate
**SST** Sea-surface temperature
**SST** Supersonic transport (aircraft)
**TTAPS** Turco, Toon, Ackerman, Pollack, Sagan (nuclear winter)
**UNCED** United Nations Conference on Environment and Development
**UNCOD** United Nations Conference on Desertification
**UNECE** United Nations Economic Commission for Europe
**UNEP** United Nations Environment Program
**USAID** United States Agency for International Development
**UV-A** Ultraviolet A
**UV-B** Ultraviolet B
**UV-C** Ultraviolet C
**VEI** Volcanic explosivity index
**WMO** World Meteorological Organization

# 1

# Setting the scene

The nations of the world came together in Rio de Janeiro in June 1992 at the United Nations Conference on Environment and Development (UNCED)—dubbed the Earth Summit—to try to reach consensus on the best way to slow down, halt and eventually reverse ongoing environmental deterioration. The Summit represented the culmination of two decades of development in the study of environmental issues, initiated at the United Nations Conference on the Human Environment held in Stockholm in 1972. Stockholm was the first conference to draw worldwide public attention to the immensity of environmental problems, and because of that it has been credited with ushering in the modern era in environmental studies (Haas *et al.* 1992).

The immediate impact of the Stockholm conference was not sustained for long. Writing in 1972, the climatologist Wilfrid Bach expressed concern that public interest in environmental problems had peaked and was already waning. His concern appeared justified as the environmental movement declined in the remaining years of the decade, pushed out of the limelight in part by growing fears of the impact of the energy crisis. Membership in environmental organizations—such as the Sierra Club or the Wilderness Society—which had increased rapidly in the 1960s, declined slowly, and by the late 1970s the environment was seen by many as a dead issue (Smith 1992). In the 1980s, however, there was a remarkable resurgence of interest in environmental issues, particularly those involving the atmospheric environment. The interest was broad, embracing all levels of society, and held the attention of the general public, plus a wide spectrum of academic, government and public-interest groups.

Most of the issues were not entirely new. Some, such as acid rain, the enhanced greenhouse effect, atmospheric turbidity and ozone depletion, had their immediate roots in the environmental concerns of the 1960s, although the first two had already been recognized as potential problems in the nineteenth century. Drought and famine were problems of even longer standing. Contrasting with all of these was nuclear winter—a product of the Cold War—which remained an entirely theoretical problem, but potentially no less deadly because of that.

Diverse as these issues were, they had a number of features in common. They were, for example, global or at least hemispheric in magnitude, large scale compared to the local or regional environmental problems of earlier years. All involved human interference in the atmospheric component of the earth/atmosphere system, and this was perhaps the most important element they shared. They reflected society's ever-increasing ability to disrupt environmental systems on a large scale.

These issues are an integral part of the new environmentalism which has emerged in the early 1990s. It is characterized by a broad, global outlook, increased politicization—marked particularly by the emergence of the so-called Green Parties in Europe—and a growing environmental consciousness which takes the form of waste reduction, prudent use of resources and the development of environmentally safe products (Marcus and Rands 1992). It is also a much more aggresive environmentalism, with certain organizations—Green-peace and Earth First, for example—using direct action in addition to debate and discussion to draw attention to the issues (Smith 1992).

Another characteristic of this new environmentalism is a growing appreciation of the economic and political components in environmental issues, particularly as they apply to the problems arising out of the economic disparity between the rich and poor nations. The latter need economic development to combat the poverty, famine and disease that are endemic in many Third World countries, but do not have the capacity to deal with the environmental pressures which development brings. The situation is complicated by the perception among the developing nations that imposition of the environmental protection strategies proposed by the industrial nations is not only forcing them to pay for something they did not create, but is also likely to retard their development,

Development issues were included in the Stockholm conference in 1972, but they were clearly of secondary importance at that time, well behind all of the environmental issues discussed.

*Table 1.1* Treaties signed at the world environment meetings in Rio de Janeiro—June 1992

*United Nations Conference on Environment and Development (UNCED)*

Government treaties and other documents

**The Rio Declaration** 27 principles – key elements of the political agendas of both industrialized and developing nations.

**Convention on Climate Change** includes as an objective the stabilization of greenhouse gas concentrations, but no agreement on specific emission targets or dates.

**Convention on Biodiversity** goals include conservation and sustainable use of biological diversity, plus fair sharing of products made from genestocks.

**Statement of Forest Principles** not a treaty, but a statement of 17 non-binding principles for the protection and sustainable development of all forests – tropical, temperate and boreal.

**Agenda 21** attempts to embrace the entire environment and development agenda. Consists of four sections – social and economic dimensions, conservation and management of resources for development, strengthening the role of major groups, means of implementation – and forty chapters covering all aspects of the environment, including issues such as climate change, ozone depletion, transboundary air pollution, drought and desertification, all of which have a strong atmospheric element.

*Global Forum*

Nongovernmental organization (NGO) treaties and other documents

**Earth Charter** a short statement of eight principles for sustainable development intended to parallel the Rio Declaration.

*Treaty Groupings*

**NGO cooperation and institution-building cluster** includes treaties on technology, sharing of resources, poverty, communications, global decision making and proposals for NGO action.

**Alternative economic issues cluster** includes treaties on alternative economic models, trade, debt, consumption and lifestyles.

**Major environmental issues cluster** includes treaties on climate, forests, biodiversity, energy, oceans, toxic waste and nuclear waste.

**Food production cluster** includes treaties on sustainable agriculture, food security, fisheries.

**Cross-sectorial issues cluster** includes treaties on racism, militarism, women's issues, population, youth, environmental education, urbanization and indigenous peoples.

*Source:* Compiled from information in Parson *et al.* (1992)

Fifteen years later, the report of the World Commission on Environment and Development—commonly called the Brundtland Commission after its chairwoman, Gro Harlem Brundtland—firmly combined economy and environment through its promotion of 'sustainable development', a concept which required development to be both economically and environmentally sound so that the needs of the world's current population could be met without jeopardizing those of future generations. The Brundtland Commission also proposed a major international conference to deal with such issues. This led directly to the Earth Summit in Rio de Janeiro in 1992, and its parallel conference of non-governmental organizations (NGOs)—the Global Forum.

The theme of economically and environmentally sound development was carried through the Summit to the final Rio Declaration of global principles and to Agenda 21, the major document produced by the conference, and basically a blueprint for sustainable development into the twenty-first century. That theme also appeared in other documents signed at Rio, including a Framework Convention on Climate Change brought on by concern over global warming, a Biodiversity Convention which combined the preservation of natural biological diversity with sustainable development of biological resources, and a Statement of Forest Principles aimed at balancing the exploitation and conservation of forests. Discussions and subsequent agreements at the Global Forum included an equally wide range of concerns (see Table 1.1).

There can be no assurance that these efforts will be successful. Even if they are, it will be some time—probably decades—before the results become apparent, and success may have been limited already by the very nature of the various treaties and conventions. For example, both the Rio Declaration and Agenda 21 were the result of compromise among some 150 nations. Attaining sufficient common ground to make this possible inevitably weakened the language and content of the documents, leaving them open to interpretation and therefore less likely to be effective (Pearce 1992b). The failure of the developed nations to commit new money to allow the proposals contained in the documents to go ahead is also a major concern (Pearce 1992a). Perhaps this lack of financial commitment is a reflection of the recessionary conditions of the early 1990s, but without future injections of funds from the developed nations, the necessary environmental strategies will not be implemented, and Third World economic growth will continue to be retarded (Miller 1992). Other documents are little more than statements of concern with no legal backing. The forestry agreement, for example, is particularly weak, largely as a result of the unwillingness of the developing nations to accept international monitoring and supervision of their forests (Pearce 1992a). The end product remains no more than a general statement acknowledging the need to balance the exploitation of the forests with their conservation. Similarly, the Framework Convention on Climate Change, signed only after much conflict among the participants, was much weaker than had been hoped—lacking even specific emission reduction targets and deadlines (Warrick 1993).

Faced with such obstructions to progress from the outset, the Rio Summit is unlikely to have much direct impact in the near future. When change does come it is unlikely to come through such wide-ranging international conferences where rhetoric often exceeds commitment. It is more likely to be achieved initially by way of issue-specific organizations, and the Earth Summit contributed to progress in that area by establishing a number of new institutions—the Sustainable Development Commission, for example—and new information networks. By bringing politicians, non-governmental organizations and a wide range of scientists together, and publicizing their activities by way of more than 8,000 journalists, the Summit also added momentum to the growing concern over global environmental issues, wiithout which future progress will not be possible.

## THE IMPACT OF SOCIETY ON THE ENVIRONMENT

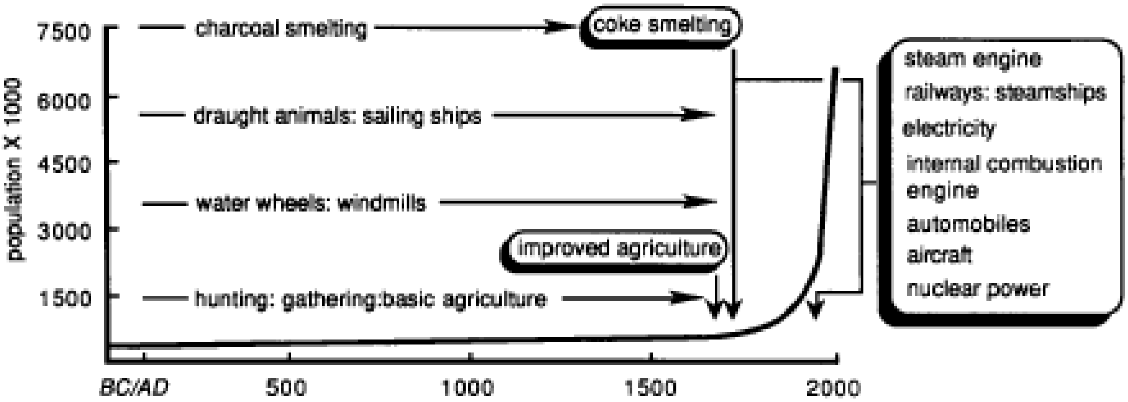
Society's ability to cause significant disruption in the environment is a recent phenomenon, strongly influenced by demography and technological development. Primitive peoples, for example, being few in number, and operating at low energy levels with only basic tools, did very little to alter their environment. The characteristically low natural growth rates of the

*Table 1.2* Energy use, technological development and the environment

| *Time* | *Daily per capita energy consumption (kcals)* | *Main sources* | *Use* | *Environmental impact* |
|---|---|---|---|---|
| 1,000,000 BC | 2,000 | Food; human muscle | Daily life | Minimal |
| 100,000 BC | 4–5,000 | Food; fire; simple tools | Heating; cooking; hunting | Local and short term; mainly vegetation destruction and reduction of animal population |
| 5,000 BC | 12,000 | Animals; agricultural produce | Transportation; cultivation; construction | Local and longer term; mainly in agricultural hearths (e.g. Egypt, Mesopotamia); natural vegetation replaced by cultivated crops; aquatic environment altered; beginnings of soil degradation |
| AD 1400 | 26,000 | Wind; water; coal; windmills; waterwheels | Mechanical operations; pumping water; sawmilling; grinding grain; transportation | Local and longer term or permanent; natural vegetation removed; urban air pollution already common |
| AD 1800 | 50,000 | Coal; steam engine | Mechanical operations; industrial processes; transportation | Local and regional and permanent; major landscape changes begin; air and water pollution common in industrial areas |
| AD 1980 | 300,000 | Fossil fuels; nuclear energy; internal combustion engine; electricity | Mechanical operations; industrial processes; transportation; social and cultural development | Local; regional and global; permanent and perhaps irreversible air, water and soil deterioration on global scale; acid rain; enhanced greenhouse effect; ozone depletion; increased atmospheric turbidity |

*Source:* Compiled from data in Biswas (1974), Kleinbach and Salvagin (1986)

*Figure 1.1* World population growth and significant technological developments




hunting and gathering groups who inhabited the earth in prehistoric times ensured that populations remained small. This, combined with their nomadic lifestyle, and the absence of any mechanism other than human muscle by which they could utilize the energy available to them, limited their impact on the environment. In truth, they were almost entirely dominated by it. When it was benign, survival was assured. When it was malevolent, survival was threatened. Population totals changed little for thousands of years, but slowly, and in only a few areas at first, the dominance of the environment began to be challenged. Central to that challenge was the development of technology which allowed the more efficient use of energy (see Table 1.2). It was the ability to concentrate and then expend larger and larger amounts of energy that made the earth's human population uniquely able to alter the environment. The ever-growing demand for energy to maintain that ability is at the root of many modern environmental problems (Biswas 1974).

The level of human intervention in the environment increased only slowly over thousands of years, punctuated by significant events which helped to accelerate the process (see Figure 1.1). Agriculture replaced hunting and gathering in some areas, methods for converting the energy in wind and falling water were discovered, and coal became the first of the fossil fuels to be used in any quantity. As late as the mid-eighteenth century, however, the environmental impact of human activities seldom extended beyond the local or regional level. A global impact only became possible with the major developments in technology and the population increase which accompanied the so-called Industrial Revolution. Since then—with the introduction of such devices as the steam engine, the electric generator and the internal combustion engine—energy consumption has increased sixfold, and world population is now five times greater than it was in 1800. The exact relationship between population growth and technology remains a matter of controversy, but there can be no denying that in combination these two elements were responsible for the increasingly rapid environmental change which began in the mid-eighteenth century. At present, change is often equated with deterioration, but then technological advancement promised such a degree of mastery over the environment that it seemed such problems as famine and disease, which had plagued mankind for centuries, would be overcome, and the quality of life of the world's rapidly expanding population would be improved infinitely. That promise was fulfilled to some extent, but, paradoxically, the same technology which had solved some of the old problems, exacerbated others, and ultimately created new ones.

## THE RESPONSE OF THE ENVIRONMENT TO HUMAN INTERFERENCE

The impact of society on the environment depends not only on the nature of society, but also on the nature of the environment. Although it is common to refer to 'the' environment, there are in fact many environments, and therefore many possible responses to human interference. Individually, these environments vary in scale and complexity, but they are intimately linked, and in combination constitute the whole earth/atmosphere system (see Figure 1.2). Like all systems, the earth/atmosphere system consists of a series of inter-related components or subsystems, (see Figure 1.3) ranging in scale from microscopic to continental, and working together for the benefit of all. Human interference has progressively disrupted this beneficial relationship. In the past, disruption was mainly at the sub-system level—contamination of a river basin or pollution of an urban environment, for example—but the integrated nature of the system, coupled with the growing scale of interference caused the impact to extend beyond individual environments to encompass the entire system.

In material terms the earth/atmosphere is a closed system, since it receives no matter (other than the occasional meteorite) from beyond its boundaries. The closed nature of the system is of considerable significance, since it means that the total amount of matter in the system is fixed. Existing resources are finite; once they are used up they cannot be replaced. Some elements—for example, water, carbon, nitrogen, sulphur—can be used more than once because of the existence of efficient natural recycling processes which clean, repair or reconstitute them. Even they are no longer immune to disruption, however. Global warming is in large part a reflection of the inability of the carbon cycle to cope with the additional carbon dioxide introduced into the system by human activities.

The recycling processes and all of the other sub-systems are powered by the flow of energy through the system. In energy terms the earth/atmosphere system is an open system, receiving energy from the sun and returning it to space after use. When the flow is even and the rates of input and output of energy are equal, the system

*Figure 1.2* Schematic diagram of the earth/atmosphere system

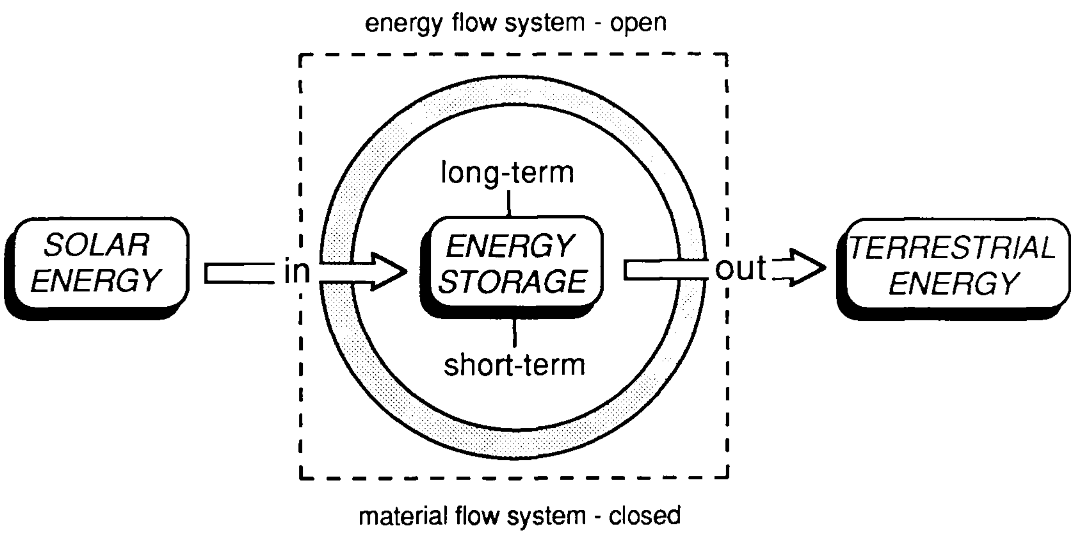


*Figure 1.3a* Schematic diagram of a natural subsystem—a lake basin

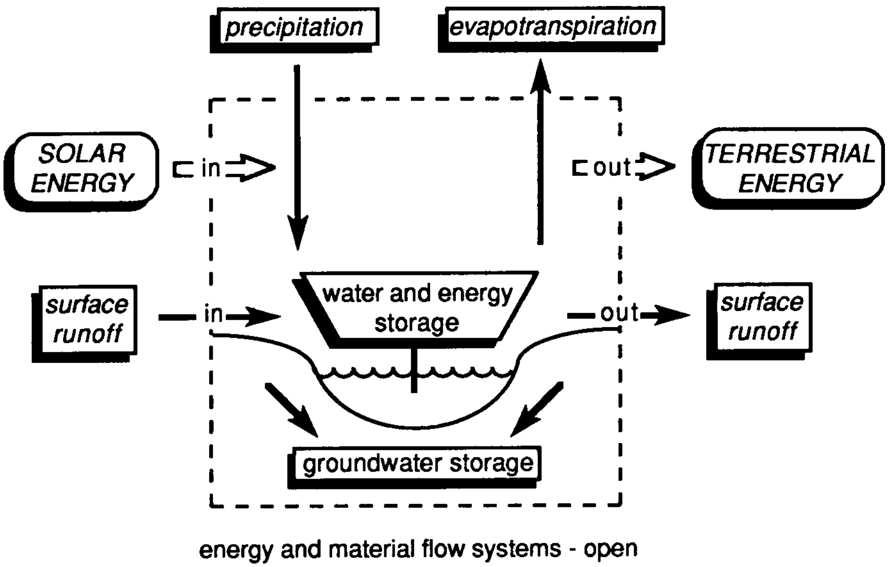
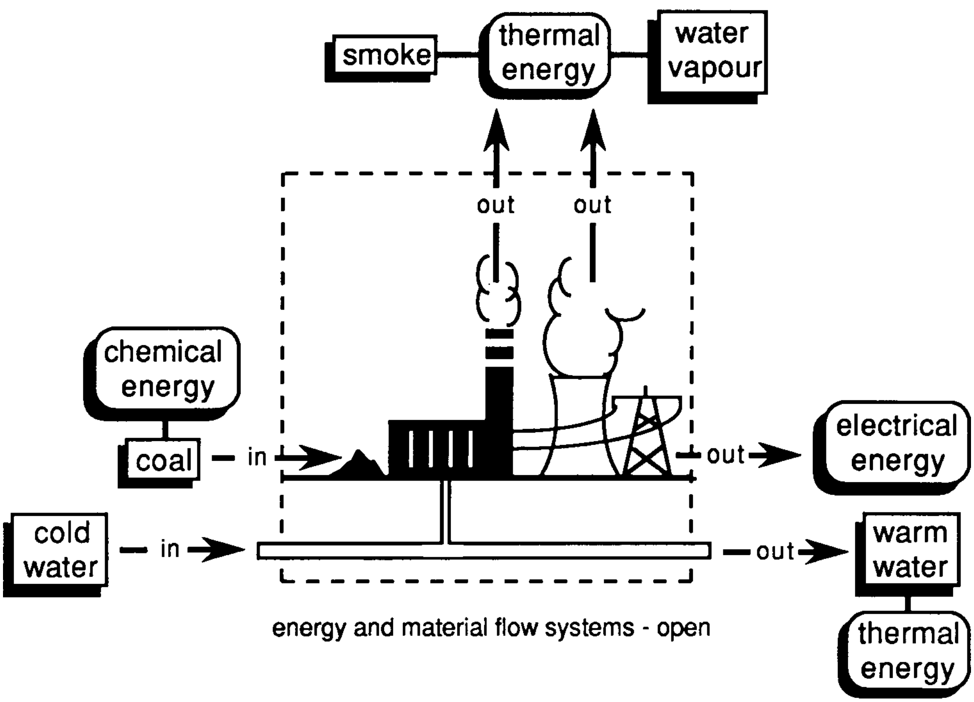



*Figure 1.3b* Schematic diagram of a subsystem of anthropogenic origin—a thermal electric power plant



is said to be in a steady state. Because of the complexity of the earth/atmosphere system, the great number of pathways available to the energy and the variety of short and long-term storage facilities that exist, it may never actually reach that condition. Major excursions away from a steady state in the past may be represented by such events as the Ice Ages, but in most cases the responses to change are less obvious. Changes in one element in the system, tending to produce instability, are countered by changes in other elements which attempt to restore balance. This tendency for the components of the environment to achieve some degree of balance has long been recognized by geographers, and referred to as environmental equilibrium. The balance is never complete, however. Rather, it is a dynamic equilibrium which involves a continuing series of mutual adjustments among the elements that make up the environment. The rate, nature and extent of the adjustments required will vary with the amount of disequilibrium introduced into the system, but in every environment there will be periods when relative stability can be maintained with only minor adjustments. This inherent stability of the environment tends to dampen the impact of changes even as they happen, and any detrimental effects that they produce may go unnoticed. At other times, the equilibrium is so disturbed that stability is lost, and major responses are required to restore the balance. Many environmentalists view the present environmental deterioration as the result of human interference in the system at a level which has pushed the stabilizing mechanisms to their limits, and perhaps beyond.

Running contrary to this is the much less pessimistic point of view expressed by James Lovelock and his various collaborators in the Gaia hypothesis (Lovelock 1972; Lovelock and Margulis 1973). First developed in 1972, and named after an ancient Greek earth-goddess, the hypothesis views the earth as a single organism in which the individual elements exist together in a symbiotic relationship. Internal control mechanisms maintain an appropriate level of stability. Thus, it has much in common with the concept of environmental equilibrium. It goes further, however, in presenting the biocentric view that the living components of the environment are capable of working actively together to provide and retain optimum conditions for their own survival. Animals, for example, take up oxygen during respiration and return carbon dioxide to the atmosphere. The process is reversed in plants, carbon dioxide being absorbed and oxygen released. Thus, the waste product from each group becomes a resource for the other. Working together over hundreds of thousands of years, these living organisms have combined to maintain oxygen and carbon dioxide at levels capable of supporting their particular forms of life. This is one of the more controversial aspects of Gaia, flying in the face of majority scientific opinion—which, since at least the time of Darwin, has seen life responding to environmental conditions rather than initiating them—and inviting some interesting and possibly dangerous corollaries. It would seem to follow, for example, that existing environmental problems which threaten life—ozone depletion, for example—are transitory, and will eventually be brought under control again by the environment itself. To accept that would be to accept the efficacy of regulatory systems which are as yet unproven, particularly in their ability to deal with large scale human interference. Such acceptance would be irresponsible, and has been referred to by Schneider (1986) as 'environmental brinksmanship'.

Lovelock himself has allowed that Gaia's regulatory mechanisms may well have been weakened by human activity (Lovelock and Epton 1975; Lovelock 1986). Systems cope with change most effectively when they have a number of options by which they can take appropriate action, and this was considered one of the main strengths of Gaia. It is possible, however, that the earth's growing population has created so much stress in the environment, that the options are much reduced, and the regulatory mechanisms may no longer be able to nullify the threats to balance in the system. This reduction in the variety of responses available to Gaia may even have cumulative effects which could threaten the survival of human species. Although the idea of the earth as a living organism is a basic concept in Gaia, the hypothesis is not anthropocentric. Humans are simply one of the many forms of life in the biosphere, and whatever happens life will continue to exist, but it may not be human life. For example, Gaia includes mechanisms capable of bringing about the extinction of those organisms which adversely affect the system (Lovelock 1986). Since the human species is currently the source of most environmental deterioration, the partial or complete removal of mankind might be Gaia's natural answer to the earth's current problems.

The need for coexistence between people and the other elements of the environment, now being advocated by Lovelock as a result of his research into Gaia, has been accepted by several generations of geographers, but historically society has tended to view itself as being in conflict with the environment. Many primitive groups may have enjoyed a considerable rapport with their environment, but, for the most part, the relationship was an antagonistic one (Murphey 1973; Smith 1992). The environment was viewed as hostile, and successful growth or development depended upon fighting it, and winning. In the beginning, human inputs were relatively minor, and the results of victory could easily be accommodated in the system. Gradually, through technological advancement and, sometimes sheer weight of numbers, society became increasingly able to challenge its environment and eventually to dominate it. Natural vegetation was replaced by cultivated crops, rivers were dammed or diverted, natural resources were dug from the earth in such quantity that people began to rival geomorphological processes as agents of landscape change, and, to meet the need for shelter, nature was replaced with the built environment created by urbanization.

The environment can no longer be considered predominantly natural in most of Europe and North America. Technological innovations since the mid-eighteenth century have ensured that. In the less-developed nations of Asia, Africa and South America—where the impact of technology is less strong—pressure from large and rapidly growing populations has placed an obviously human imprint on the landscape. Extensive as it is, however, dominance is far from complete. Even after 200 years of technological development and the exponential growth of population in recent years, some geographical regions continue to resist human domination. The frozen reaches of the Arctic and Antarctic are not unaffected by human activity, but they are largely unpopulated, while habitation in the world's hot deserts is in all senses marginal.

## HUMAN ACTIVITIES AND THE ATMOSPHERIC ENVIRONMENT

Certain elements in the environment remain untamed, uncontrollable and imperfectly understood. Nowhere is this more evident than in the realm of weather and climate. Neither nineteenth nor twentieth century technology could prevent cyclones from devastating the shores of the Bay of Bengal, or hurricanes from laying waste the Caribbean. The Sahelian drought spread uncontrollably even as the first astronauts were landing on the moon. The developed nations, where society's dominance of the environment is furthest advanced, continue to suffer the depredation of tornadoes and blizzards as well as the effects of less spectacular weather events such as frost, drought, heatwaves and electrical storms, which even today are difficult to forecast. No one is immune.

It is scarcely surprising, therefore, that weather and climate are universal topics of interest at all levels of society. In most cases, concern centres on the impact of short-lived local weather events on individuals and their activities. It is very much one-sided, normally ignoring the potential that mankind has to alter its atmospheric environment. There is a growing appreciation, however, that the nature and extent of the climatological component in many current global issues is strongly influenced by human interference in the earth/atmosphere system. The evolution of this awareness has been traced by William Kellogg (1987) who points out that as long ago as the late nineteenth century, the first tentative links between fossil fuels, atmospheric carbon dioxide and world climate had been explored. The results failed to elicit much interest in the scientific community, however, and remained generally unknown to the public at large. Such a situation prevailed until the mid-1960s. From that time on the cumulative effects of a number of high-level national and international conferences, culminating in the Study of Critical Environmental Problems (SCEP) in 1970, produced a growing awareness of global environmental issues. The impact of human activities on regional and global climates was considered in the SCEP, and when it became clear that the issue was of sufficient magnitude to warrant further investigation, a follow-up conference was convened. It focused on inadvertent climate modification, and in 1971 produced a report entitled The Study of Man's Impact on Climate (SMIC). The report was recognized as an authoritative assessment of all aspects of human-induced climatic change, and it might even be considered as the final contribution to the 'critical mass' necessary to initiate the numerous and increasingly detailed studies which characterized the next two decades. The pace quickened in the late 1980s, with international conferences on various aspects of climate and the changing atmosphere being held in Montreal, Toronto, Hamburg, London and Geneva (see Chapter 8). A significant step forward was the creation in 1988 of the Intergovernmental Panel on Climate Change. Set up to evaluate global climate trends—particularly global warming—it provided major input for the discussions leading up to the signing of the convention on climate change at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992.

One of the results of all that activity was the positive identification of human interference as a common element in many of the major problems of the atmospheric environment. The information gathered during the studies is quite variable in content and approach. It has been presented in highly technical scientific reports, as well as in simple, basic articles prepared for popular consumption. The latter are particularly important as a means of disseminating information to the wider audience which past experience suggests must be educated before progress can be made in dealing with environmental problems. Because of the time and space constraints and the marketing requirements of modern journalism, however, the issues are often treated with much less intellectual rigour than they deserve. In addition, the topics are often represented as being new or modern when, in fact, most have existed in the past. Drought, acid precipitation and the greenhouse effect all result from natural processes, and were part of the earth/atmosphere system even before the human species came on the scene. Their current status, however, is largely the result of human intervention, particularly over the last 200 years, and it is the growing appreciation of the impact of this intervention that has given the issues their present high profile. One topic that can be classified as new is nuclear winter. Unlike the others, which exist at present, and have developed gradually as the accumulated results of a variety of relatively minor inputs, nuclear winter remains in the future, with an impact that can only become reality following the major catastrophic inputs of nuclear war. For many in the mid-1980s it was seen as the ultimate intervention; the ultimate blow to environmental equilibrium. Despite this, nuclear winter is no longer considered a major environmental issue by most observers. Events such as the ending of the Cold War, the break-up of the USSR and the signing of a variety of arms control agreements have reduced the potential for inter-continental nuclear war, and as a result interest in nuclear winter has declined almost to zero.

Present concerns may be seen to some extent as the most recent elements in a continuum. In the 1960s and early 1970s, the main environmental issues were those associated with pollution in its various forms. Pollution is the contamination of the components of the earth/

atmosphere system, to such an extent that normal environmental processes are adversely affected. Contamination is not always serious, however. The environment has a considerable capacity for ridding itself of pollutants, and problems only begin to arise when the input of contaminants exceeds the ability of the environment to deal with them. In modern times, this situation has become common as a result of the tremendous amount of waste generated by human activities and deposited in the environment. In the 1960s and 1970s, the most pressing popular concerns were often local in origin, dealing with such problems as urban air pollution or reduced water quality in rivers and lakes, although consideration was given to the environment as a whole in the academic and scientific community (e.g. Detwyler 1971). Along with increased concern there was also increased understanding of the environment, brought about by the development of educational programmes at all levels, from elementary school to university, and by judicious use of the media by environmental groups such as the Sierra Club, Friends of the Earth, Pollution Probe and Greenpeace. The high level at which public interest in environmental affairs was sustained during the years when improvement was marginal is in no small measure attributable to these groups.

Public pressure forced the political and industrial establishment to reassess its position on environmental quality. Oil companies, the forest products industry and even automobile manufacturers began to express concern for pollution abatement and the conservation of resources. Similar topics began to appear on political platforms, particularly in North America, and although this increased interest was regarded with suspicion, and viewed as a public relations exercise in some quarters, legislation was gradually introduced to alleviate some of the problems. By the early 1970s some degree of control seemed to be emerging. While this may have helped to reduce anxiety over environmental concerns, progress was slow, and some observers attribute the decline in interest in all things environmental at about this time to disenchantment rather than recognition that the problems were being solved (Bach 1972).

Whatever the reason, the level of concern had peaked by then, and when the oil crisis struck in 1973, energy quickly replaced environmental issues in the minds of the politicians, academics and the public at large. In the first half of the 1990s, the energy situation is perceived as less critical, the dire predictions of the economists and energy futurists have not come to pass, and the waning of interest in energy topics has been matched by a resurgence of environmental concern, particularly for problems involving the atmosphere. The new issues are global in scale and, at first sight, may appear different from those of earlier years; in fact, they share the same roots. Current topics such as acid rain and global warming are linked to the sulphurous urban smogs of two or three decades ago by society's continuing dependence on fossil fuels to meet its seemingly insatiable demand for more energy. Population pressures on land of limited carrying capacity contribute to famine and desertification much as they did in the past. The depletion of the ozone layer, associated with modern chemical and industrial technology, might be considered as only the most recent result of mankind's continual, and seemingly inherent, desire to improve its lot—all the while acting in ignorance of the environmental consequences.

Many of the problems currently of concern have causes which can be traced to ignorance of the workings of the atmosphere. This is particularly true when the impact of air pollution on climate is considered. Almost all human activities produce waste products, and some of these are introduced into the atmosphere. This presented no great problem when populations were small, and technological levels were low, for the atmosphere includes mechanisms designed to keep such emissions in check. For every process adding material to the atmosphere, there is another which works to remove or reduce the excess, either by neutralizing it or by returning it to the earth's surface. Gases, for example, may be absorbed by vegetation, neutralized by oxidation or dissolved in water and precipitated.

Particulate matter falls out of the atmosphere as a result of gravity or is washed out by precipitation. These processes have removed extraneous gases and aerosols from the atmosphere, usually quite effectively, for millions of years.

Ongoing physical and biological activities—such as volcanic eruptions, soil erosion and the combustion or decay of vegetable matter—ensure that the cleansing process is never complete, and that, in itself, is a natural part of the system. There are indications, for example, that a minimum level of extraneous material is essential for the working of such atmospheric processes as condensation and precipitation. Thus, a completely clean atmosphere may not be desirable (Barry and Chorley 1992). Desirable or not, it is unlikely to be achieved, given the present rates of gaseous and particulate emissions.

In the past, the main pollutants were natural in origin, and sources such as the oceans, volcanoes, plants and decaying organic material continue to provide about 90 per cent of the total global aerosol content (Bach 1979). Events, such as the eruption of Mount Pinatubo, indicate the continued capability of nature to provide massive volumes of pollutants, but anthropogenic sources are now paramount in many areas. Human activities provide pollutants in such amounts, and with such continuity, that the atmospheric cleansing processes have been all but overwhelmed, and a full recovery may not be possible, even after large-scale attempts to reduce emission levels.

Air pollution was one of the elements which elicited a high level of concern during the heyday of the environmental movement in the late 1960s and early 1970s. It was mainly an urban problem at that time, most common in large cities which had high seasonal heating requirements, were heavily industrialized, had large volumes of vehicular traffic or experienced combinations of all three. Even then, however, existing air pollution control ordinances were beginning to have an effect on the problem. In Pittsburgh, the introduction of smokeless fuel, and the establishment of emission controls on the iron and steel industry, brought a steady reduction in air pollution between 1945 and 1965 (Thackrey 1971). Similar improvements were achieved in London, England, where sunshine levels in the city centre increased significantly following the Clean Air Act of 1956 (Jenkins 1969). The replacement of coal by natural gas as the main heating fuel on the Canadian Prairies, in the 1950s and 1960s, allowed urban sunshine totals to increase there also (Catchpole and Milton 1976). Success was achieved mainly by reducing the atmospheric aerosol content. Little was done to reduce the gaseous component of pollution, except in California, where, in 1952, gaseous emissions from the state's millions of cars were scientifically proven to be the main source of photochemical smog (Leighton 1966). Prevention of pollution was far from complete, but the obvious improvements in visibility and sunshine totals, coupled with the publicity which accompanied the introduction of new air quality and emission controls in the 1970s, caused the level of concern over urban air pollution to decline markedly by the end of the decade.

The relationship between pollution and weather or climate is a complex one. Sometimes climatic conditions will influence the nature and extent of a pollution episode, while at other times the linkages are reversed, allowing the pollutants to instigate or magnify variations in climate. The problem of acid rain illustrates quite well the impact of atmospheric processes on the operation and distribution of a particular group of pollutants, whereas the issues of increased atmospheric turbidity and the depletion of the ozone layer illustrate the other relationship, in which pollutants cause sufficient change in the atmosphere to initiate climatic change.

The full complexity of the earth/atmosphere system is only now beginning to be appreciated, but in recent years, knowledge of the impact of human social and technological development on the atmospheric environment has grown quite dramatically. Government sponsored studies on such topics as the greenhouse effect and acid rain, along with reports by respected scientists and academics on nuclear winter and the depletion of the ozone layer, have become available. Although often quite technical, they have contained material of sufficient general interest that it could be abstracted and disseminated widely by the media. Other issues have been developed at the popular level from the outset. The interest in African drought, for example was to a large extent an emotional response to television coverage of events in Ethiopia and the success of the Live Aid concerts of 1985, although excellent academic studies of the problem have been carried out (Bryson and Murray 1977; Glantz 1977).

As more information becomes available on these global environmental issues, it is clear that the present problems have existed undetected for some time. It is also clear that the activities which produced them were entered into with the best of intentions—to improve the quality of human life—and society might even be seen as suffering from its own success. That, of course, does nothing to reduce the seriousness of the problems, but it indicates the need for extreme caution when initiating schemes which promise major advantages. The linkages in the earth/atmosphere system are such that even local or regional changes can be amplified until their impact is felt system-wide and in the modern world schemes which might conceivably alter the environment, whether immediately or ultimately, cannot be entered into lightly. Unfortunately, even in the present era of high technology, predicting the eventual reaction of the environment to a specific input is seldom possible, and changes already initiated may well be expanding and intensifying undetected to provide the makings of some future problem.

The global environmental topics to be considered in the following chapters are those which currently enjoy a high profile. They include global warming and ozone depletion—presently the leading recipients of research funding—together with acid rain and atmospheric turbidity, which now receive less attention than they did 5–10 years ago, but remain significant environmental issues. In keeping with its recently reduced status, nuclear winter is incorporated in the section on atmospheric turbidity, where it is considered as an example of the consequences of macro-scale air pollution. In contrast to these modern, high-tech problems, there is drought, a problem which has plagued mankind for centuries, causing millions of deaths and large scale environmental degradation, yet remains essentially unsolved. It deserves consideration in its own right, but as a well-established, recurring problem, it also provides a useful contrast with those of more recent origin.

Since society experiences the impact of these elements or induces change in them by way of the atmosphere, an understanding of the workings of that medium is important also. Although many processes are involved, in any discussion of global environmental issues questions of the composition of the atmosphere, its general circulation and its role in the global energy budget appear with some regularity. These topics will therefore be considered as a necessary introduction to the issues.

## SUGGESTIONS FOR FURTHER READING

Kumar, R. and Murck, B. (1992) *On Common Ground: Managing Human—Planet Relationships.* Toronto: John Wiley and Sons.

Mungall, C. and McLaren, D.J. (1990) *Planet under Stress,* Toronto: Oxford University Press.

Nisbet, E.G. (1991) *Leaving Eden: To Protect and Manage the Earth,* Cambridge: Cambridge University Press.

Starke, L. (1990) *Signs of Hope: Working towards our Common Future,* Oxford: Oxford University Press.

# 2

# The atmosphere

The atmosphere is a thick blanket of gases, containing suspended liquid and solid particles, which completely envelops the earth, and together with the earth forms an integrated environmental system. As part of this system, it performs several functions which have allowed mankind to survive and develop almost anywhere on the earth's surface. First, it provides and maintains the supply of oxygen required for life itself. Second, it controls the earth's energy budget through such elements as the ozone layer and the greenhouse effect, and—by means of its internal circulation—distributes heat and moisture across the earth's surface. Third, it has the capacity to dispose of waste material or pollutants generated by natural or human activity. Society has interfered with all of these elements, and, through ignorance of the mechanisms involved or lack of concern for the consequences of its action, has created or intensified problems which are now causing concern on a global scale.

## THE ATMOSPHERIC GASES

The constituents of the atmosphere are collectively referred to as air, although air itself is not a specific gaseous element, rather it is a mixture of individual gases each of which retains its own particular properties. Although traces of atmospheric gases have been detected well out into space, 99 per cent of the mass of the atmosphere lies within 30 km of the earth's surface, and 50 per cent is concentrated in the lowest 5 km. Most of the world's weather develops in these lower layers, but certain elements in the upper reaches of the atmosphere are also involved, and some appear as important components in the global environmental issues to be examined here.

### Oxygen and nitrogen

Ignoring for the moment the liquids and solids always present, the gaseous mixture which makes up the atmosphere has a remarkably uniform composition in the troposphere where most of the air is located. Two gases, oxygen and nitrogen, account for 99 per cent of the total by volume (see Table 2.1). Oxygen (21 per cent by volume) participates readily in chemical reactions, and provides one of the necessities of life. It is also capable of absorbing solar radiation. In contrast, nitrogen (78 per cent by volume) is basically inert, seldom becoming directly involved in atmospheric chemical or biological processes except under extraordinary circumstances. During thunderstorms, for example, the enormous energy flow in a lightning stroke may cause nitrogen to combine with oxygen to produce oxides of nitrogen. On a less spectacular, but ultimately more important level, certain soil bacteria—such as *Clostridium* and *Azobacter*—along with those found in the root nodules of leguminous plants, are capable of fixing the atmospheric nitrogen essential for the creation of the complex nitrogen compounds found in all forms of life on earth (Steila 1976).

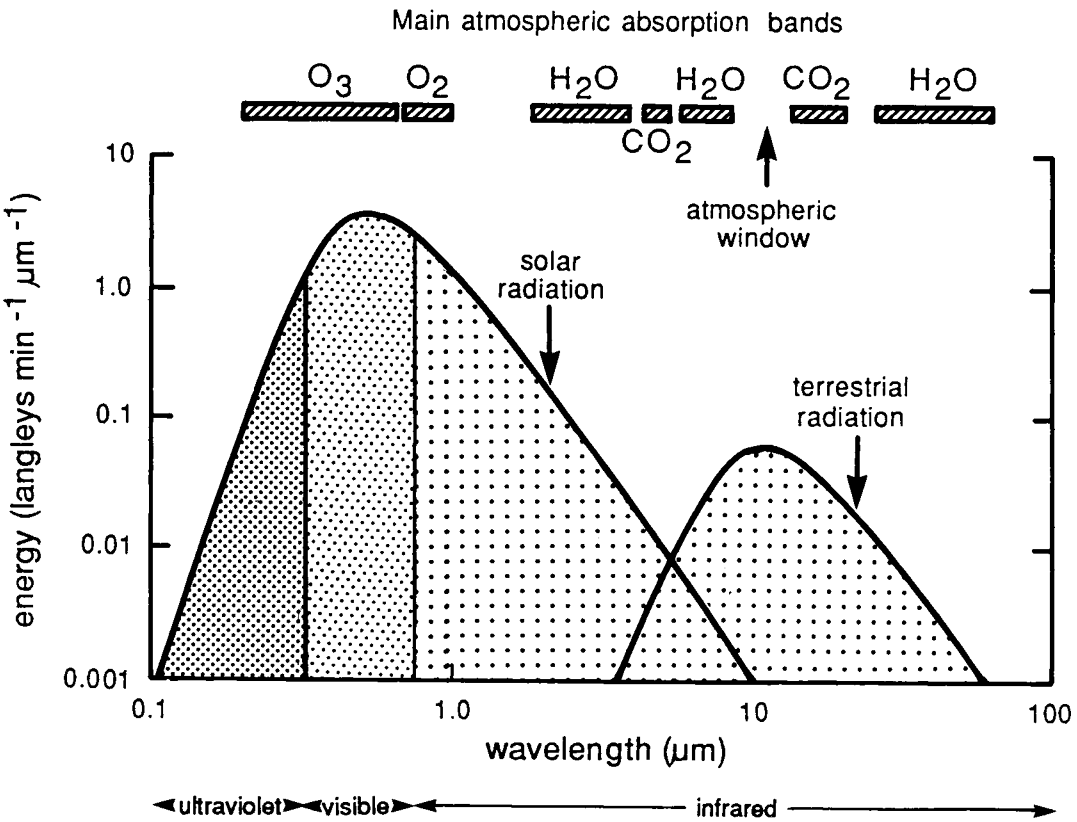
Efficient recycling processes maintain the volume of both gases, and turbulent mixing

*Table 2.1* Average gaseous composition of dry air in the troposphere

| *Gas* | *Per cent by volume* | *Parts per million* |
|---|---|---|
| Nitrogen | 78.08 | 780,840.00 |
| Oxygen | 20.95 | 209,500.00 |
| Argon | 0.93 | 9,300.00 |
| Carbon dioxide | 0.0345 | 345.00 |
| Neon | 0.0018 | 18.00 |
| Helium | 0.00052 | 5.20 |
| Methane | 0.00014 | 1.40 |
| Krypton | 0.00010 | 1.00 |
| Hydrogen | 0.00005 | 0.50 |
| Xenon | 0.000009 | 0.09 |
| Ozone | Variable | Variable |

ensures that they are evenly distributed. There is no evidence that the relative levels of oxygen and nitrogen are changing significantly, although there have been measurable changes in the proportions of other gases in the atmosphere. Changes in the nature of oxygen, however, are involved in the depletion of the ozone layer, now recognised as one of the world's major environmental issues. Oxygen can exist in the atmosphere as atomic, diatomic or triatomic oxygen, depending upon the number of atoms in a molecule. The most common form is diatomic oxygen ($O_2$), but the triatomic form called ozone ($O_3$), created through the combination of the other two types, is present in the upper atmosphere. Ozone is also found close to the

*Figure 2.1* S pectral distribution of solar and terrestrial radiation. Solar radiation is represented by a curve for a black body at 6000°K and terrestrial by a black body at 300°K. A black body is a perfect radiator or absorber of energy



surface, on occasion—usually as a product of air pollution—but its main location is in the upper atmosphere, where it effectively filters out short-wave solar radiation at the ultraviolet end of the spectrum. Any change in ozone levels, allowing an increase or decrease in the transmission of radiation, would therefore cause disruption of the earth's energy budget, and lead to alterations in temperature levels and distribution patterns. It is also estimated that a reduction in ozone in the upper atmosphere would allow an increase in the incidence of skin cancer in humans, as well as genetic mutation in lower level organisms as a result of the increase in the proportion of ultraviolet radiation reaching the earth's surface (Dotto and Schiff 1978).

### The minor gases and the greenhouse effect

Although gases other than oxygen or nitrogen account for only about 1 per cent of the atmospheric total, they have an influence quite out of proportion to their volume. The most abundant of these is argon at 0.93 per cent by volume, but it is inert. Another of these minor gases, carbon dioxide has a much more active role in environmental processes. It comprises only 0.03 per cent by volume, yet it makes a significant contribution to the heating of the atmosphere, and is a major participant in the process of photosynthesis by which sugars, starches and other complex organic compounds are produced in plants.

The atmosphere is quite selective in its response to solar radiation. It is transparent to high energy, short-wave radiation, such as that from the sun, but partially opaque to the lower energy, long-wave radiation emanating from the earth's surface. For example, a major proportion of the radiation in the visible range of the spectrum, between 0.3 and 0.7 micrometres (μm), is transmitted through to the surface without losing its high energy content (see Figure 2.1). Once it arrives it is absorbed, the surface heats up, and begins to emit terrestrial long-wave radiation back into the atmosphere. This radiation, from the infrared end of the spectrum—with wavelengths between 1–30 μm—is captured, and the temperature of the atmosphere rises. The capture of the outgoing terrestrial radiation is effected largely by water vapour and carbon dioxide, along with methane and traces of about twenty other gases, which together are called the greenhouse gases. The whole process was labelled the greenhouse effect since the gases, by trapping the heat, appeared to work in much the same way as the glass in a greenhouse. The name remains in common use, although it is now generally accepted that the processes involved are not exactly the same. For example, the glass in the greenhouse acts as a physical barrier to the transfer of energy. There is no such barrier in the atmosphere. Whatever the accuracy of the analogy, the selective nature of the atmosphere in its response to radiation is of supreme importance to the earth's energy budget.

Since the greenhouse effect depends upon carbon dioxide and the other gases in the atmosphere, it follows that any change in these gases, including their relative concentration, will have an effect on the intensity of the greenhouse effect. Changes in greenhouse gas levels in the past were brought about by natural processes, but, since the middle of the nineteenth century, human activities have had a major role in increasing the intensity of the greenhouse effect through the production of higher volumes of carbon dioxide, methane and a number of other greenhouse gases. Concern over the impact of such changes has promoted the intensification of the greenhouse effect to its present position as a significant environmental issue.

### Oxides of sulphur and nitrogen

There are many other gases which from time to time become constituents of the atmosphere. These include sulphur dioxide, oxides of nitrogen, hydrogen sulphide and carbon monoxide, along with a variety of more exotic hydrocarbons, which even in small quantities can be harmful to the environment. All of these gases are natural constituents of the atmosphere, released as a result of biological activity, created during volcanic eruptions or produced by natural wood and grass fires. Increasingly, however, their presence is associated with pollution from industrial or vehicular sources. In recent years, concern has centred on the widespread dissemination and detrimental environmental impact of some of these gases. Increasing industrial activity, and the continued reliance on fossil fuels as energy sources, has caused a gradual, but steady, growth in the proportion of sulphur and nitrogen oxides in the atmosphere over the past 2–3 decades. In combination with atmospheric water, these gases—whether natural or anthropogenic in origin—are the main ingredients of acid rain. Anthropogenically produced acid rain is commonly many times more acid than its natural conterpart, however, and has been identified as a major cause of damage to aquatic and terrestrial ecosystems in North America and Europe. Although it has received less attention in recent years, it remains a significant environmental problem in the industrialized nations of the world, and there is growing evidence that areas currently little affected—the southern hemisphere, for example—may not always be immune.

## WATER IN THE ATMOSPHERE

The creation of acid rain would not be possible without water, another of the major natural constituents of the atmosphere. Lists of the principal gases in the atmosphere—such as Table 2.1—commonly refer to dry air, but the atmosphere is never completely dry. The proportion of water vapour in the atmosphere, in the humid tropics, may be as much as 4 per cent by volume, and even above the world's driest deserts there is water present, if only in fractional amounts. At any one time, the total volume of water in the atmosphere is relatively small, and, if precipitated completely and evenly across the earth's surface, would produce the equivalent of no more than 25 mm of rainfall (Barry and Chorley 1992). In reality, the distribution is very

*Figure 2.2* The hydrologic cycle

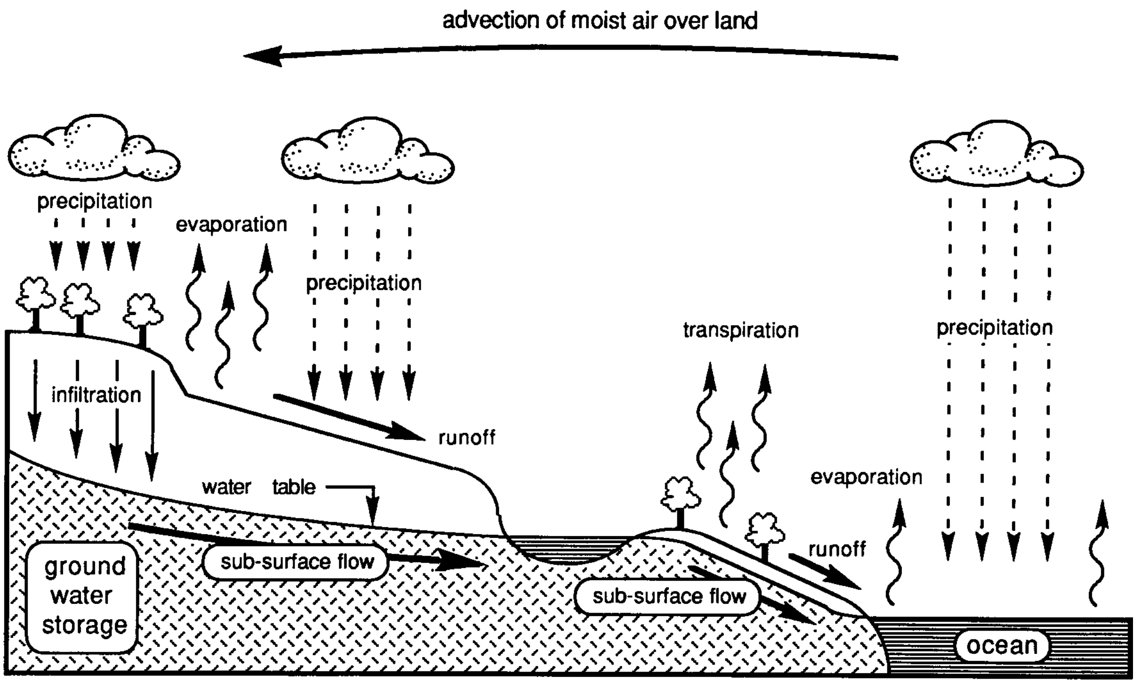
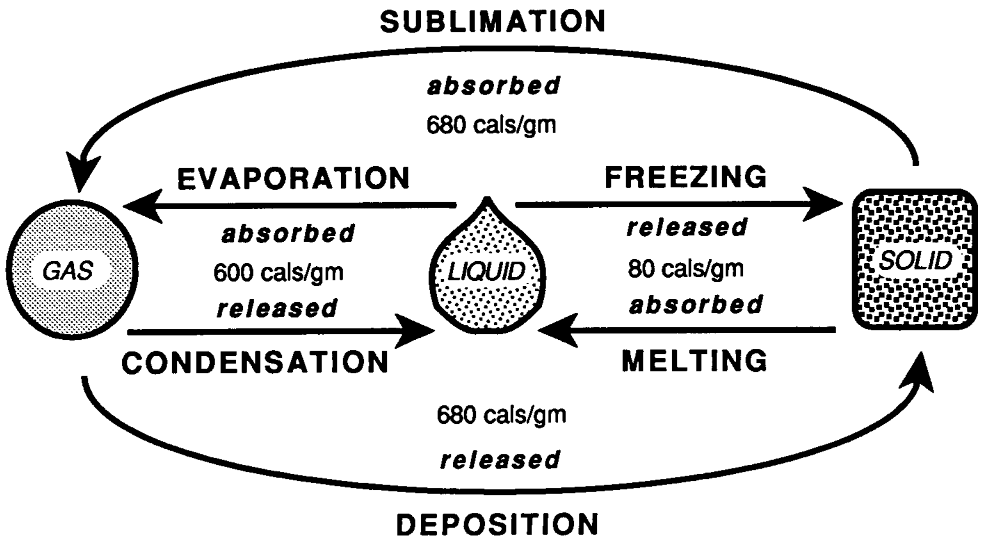


*Figure 2.3* Energy transfer during the change in state of water




uneven, as a result of regional variability in the dynamic processes which produce precipitation. Intense thunderstorms can yield 25 mm of precipitation in a matter of minutes, whereas the same amount may take several months, or even years, to accumulate under more stable atmospheric conditions. Variations such as these account for annual precipitation totals which range from virtually nothing, in some of the world's deserts, to as much as 4,000 mm, in the monsoon lands of the tropics. Precipitation in excess of the quantities normally in the air is made possible by the hydrologic cycle, which circulates water through the earth/atmosphere system, and regularly replenishes the atmospheric reservoir (see Figure 2.2).

Water is unique among the constituents of the atmosphere in that it is capable of existing as solid, liquid or gas, and of changing readily from one state to another. It becomes involved in energy transfer as a result of these changes. For example, energy absorbed during the conversion of liquid water to water vapour is retained by the latter, in the form of latent heat, until the process is reversed. The stored energy is then released (see Figure 2.3). The water vapour may travel over great distances in the atmosphere in the period between the absorption and re-release of the energy, and in this way energy absorbed in one location is transported elsewhere in the system.

Water is also involved in the earth's energy budget through its ability to absorb and reflect radiation. As vapour, it contributes to the greenhouse effect by absorbing terrestrial radiation, whereas in its liquid and solid forms it can be highly reflective. As clouds in the air or snow on the ground, it may reflect as much as 90 per cent of the solar radiation it intercepts. That radiation, reflected back into space, makes no contribution to the energy requirements of the system. In contrast, clouds can also help to retain terrestrial radiation by reflecting it back to the surface.

Water is an integral part of many global environmental issues such as drought, desertification and acid rain. In addition, because of its role in the earth's energy budget, any change in the distribution of water in the earth/ atmosphere system might well augment or diminish the impact of other elements such as the greenhouse effect or ozone depletion which, in whole or in part, make their presence felt through that budget.

## ATMOSPHERIC AEROSOLS

In addition to the gaseous components of the atmosphere and the water in its various forms, there are also solid or liquid particles dispersed in the air. These are called aerosols, and include dust, soot, salt crystals, spores, bacteria, viruses and a variety of other microscopic particles. Collectively, they are often regarded as equivalent to air pollution, although many of the materials involved are produced naturally by volcanic activity, forest and grass fires, evaporation, local atmospheric turbulence, and biological processes. The proportion of particulate matter in the atmosphere has increased from time to time in the past, sometimes dramatically, but in most cases the atmosphere's built-in cleansing mechanisms were able to react to the changes, and the overall impact was limited in extent and duration. When the island of Krakatoa exploded in 1883, for example, it threw several cubic kilometres of volcanic dust into the atmosphere. Almost all of it is thought to have returned to the earth's surface in less than five years, as a result of particle coagulation, dry sedimentation and wash-out by precipitation (Ponte 1976). The 'red-rain' which occasionally falls in northern Europe is a manifestation of this cleansing process, being caused when dust from the Sahara is carried up into the atmosphere by turbulence over the desert, and washed out by precipitation in more northerly latitudes (Tullett 1984). Thus, the atmosphere can normally cope with the introduction of aerosols by natural processes. Cleansing is never complete, however. There is always a global background level of atmospheric aerosols which reflects a dynamic balance between the output from natural processes and the efficiency of the cleansing mechanisms. Data collected over the past several decades suggest that the background level is rising, as a result of the increasing volume of aerosols of anthropogenic origin, although the evidence is sometimes contradictory (Bach 1979).

Measurements since the 1930s—in locations as far apart as Mauna Loa in Hawaii, Davos in Switzerland and the Russian Caucasus—show a sharp rise in the atmosphere's aerosol content, or turbidity as it is called. Results from such stations, located at high altitudes, and relatively remote from the world's main industrial areas, are considered representative of global background aerosol levels. Recent observations of increasing cold season atmospheric pollution in high latitudes—the so-called 'Arctic haze'—are also considered indicative of rising global levels (Environment Canada 1987). Volcanic activity may also have provided some natural enhancement in recent years, but the close correspondence between elevated turbidity levels and such indicators of human development as industrialization and energy use suggests that anthropogenic sources are major contributors. Some studies claim, however, that the observations are insufficient to allow the human contribution to increased turbidity to be identified (Bach 1979).

Any increase in the turbidity of the atmosphere should cause global temperatures to decline, as the proportion of solar radiation reaching the earth's surface is reduced by scattering and absorption. In addition, the condensation of water vapour around atmospheric aerosols would lead to increased cloudiness and a further reduction in the transmission of incoming radiation. This approach has been used to explain the decline in global average temperatures which occurred between 1940 and 1960, and in the 1970s it was seen by some as the mechanism by which a new ice age would be initiated (Ponte 1976). Such thinking is also central to the concept of nuclear winter which would be caused by a rapid temperature decline following the injection of large volumes of aerosols into the atmosphere (Bach 1986).

Providing a dissenting opinion are those who claim that an increase in atmospheric aerosols would have less serious results. The reduction in insolation is accepted, but it is also considered that there would be a concomitant reduction in the amount of terrestrial radiation escaping into space, which would offset the cooling, and perhaps result in some warming of the lower atmosphere. The overall effects would depend very much on the altitude and distribution of the aerosols (Mitchell 1975).

Contradictory conclusions, such as these—drawn from the same basic information—are to be expected in climatological studies. They reflect the inadequacy of existing knowledge of the workings of the earth/atmosphere system, and, although research and technological development is changing that situation, it remains a major element in restricting society's response to many global issues.

## THE VERTICAL STRUCTURE OF THE ATMOSPHERE

Although its gaseous constituents are quite evenly mixed, the atmosphere is not physically uniform throughout. Variations in such elements as temperature and air pressure provide form and structure in what would otherwise be an amorphous medium. The commonly accepted delineation of the atmosphere into a series of layers, for example, is temperature based (see Figure 2.4). The lowest layer is the troposphere. It ranges in thickness from about 8 km at the poles to 16 km at the equator, mainly as a result of the difference in energy budgets at the two locations, and temperatures characteristically decrease with altitude at a rate of 6.5°C per kilometre within it—the tropospheric lapse rate. Temperatures at the upper edge of the troposphere average between -50 and -60°C, but in equatorial regions, where it reaches its greatest altitude, values may be as low as -80°C. The tropospheric lapse rate is, in fact, quite variable, particularly close to the surface. Such variations regularly produce instability in the system, and help to make the troposphere the most turbulent of the atmospheric layers.

The troposphere contains as much as 75 per cent of the gaseous mass of the atmosphere, plus almost all of the water vapour and other aerosols (Barry and Chorley 1992). It is also the

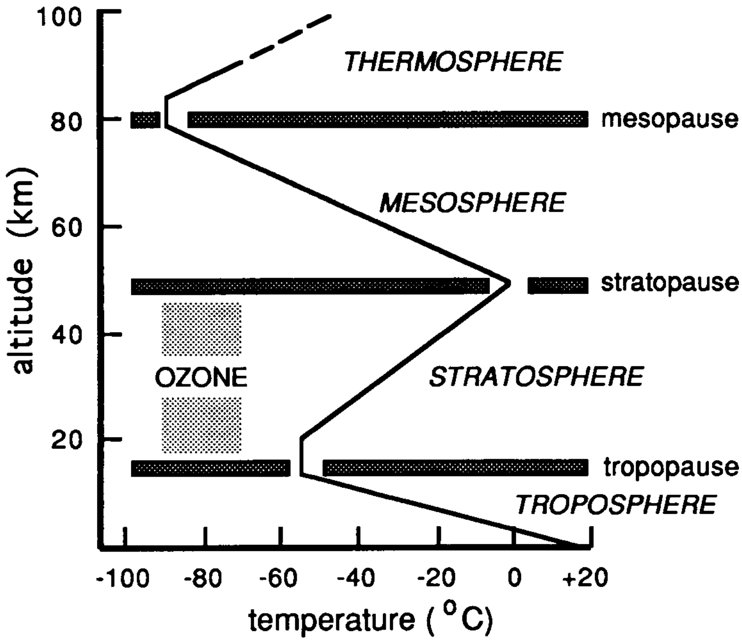



*Figure 2.4* The vertical structure of the atmosphere and its associated temperature profile

zone in which most weather systems develop, and run their course. These factors, together with the high level of human intervention in this part of the atmosphere, ensure that many of the global environmental problems of current concern—including acid rain, atmospheric turbidity and global warming—have their origins or reach their fullest extent in the troposphere.

The tropopause marks the upper limit of the troposphere. Beyond it, in the stratosphere, isothermal conditions prevail; temperatures remain constant, at or about the value reached at the tropopause, up to an altitude of about 20 km. Above that level the temperature begins to rise again reaching a maximum some 50 km above the surface, at the stratopause, where temperatures close to or even slightly above 0°C are common. This is caused by the presence of ozone, which absorbs ultraviolet radiation from the sun, and warms the middle and upper levels of the stratosphere, creating a temperature inversion. The combination of that inversion with the isothermal layer in the lower stratosphere creates very stable conditions, and the stratosphere has none of the turbulence associated with the troposphere. This has important implications for the environment. Any foreign material introduced into the stratosphere tends to persist there much longer than it would if it had remained below the tropopause. Environmental problems such as ozone depletion and atmospheric turbidity are aggravated by this situation. Much of the impact of nuclear winter would result from the penetration of the tropopause by the original explosions, and the consequent introduction of large volumes of pollutants into the stratosphere.

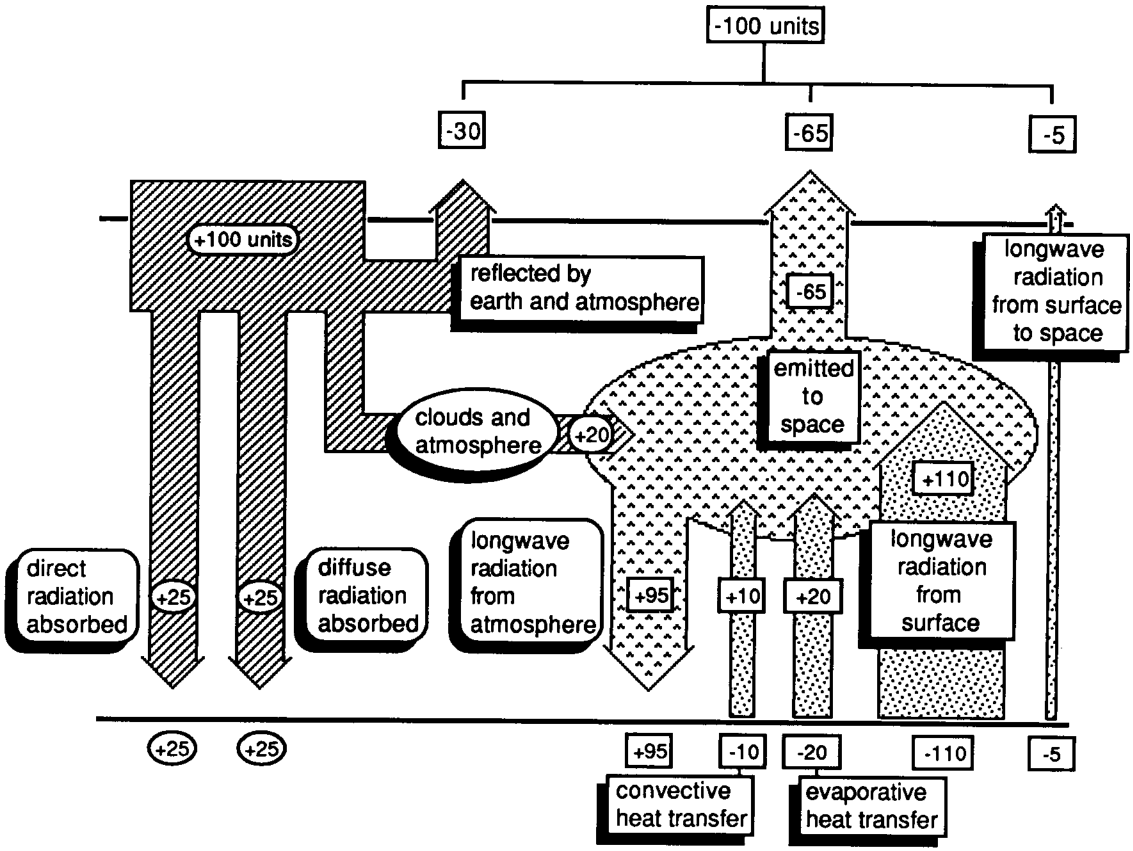
Temperatures again decrease with height above the stratopause and into the mesosphere, falling as low as -100°C at the mesopause, some 80 km above the surface. The thermosphere stretches above this altitude, with no obvious outer limit. In this layer, temperatures may exceed 1,000°C, but such values are not directly comparable to temperatures in the stratosphere and troposphere, because of the rarified nature of the atmosphere at very high altitudes. Knowledge of the nature of the thermosphere, and its internal processes, is far from complete, and linkages between the upper and lower layers of the atmosphere remain speculative. For the climatologist and environmentalist the most important structural elements of the atmosphere are the troposphere and stratosphere. The main conversion and transfer of energy in the earth/atmosphere system takes place within these two layers of the lower atmosphere, and interference with the mechanisms involved has contributed to the creation and intensification of current problems in the atmospheric environment.

## THE EARTH'S ENERGY BUDGET

Virtually all of the earth's energy is received from the sun in the form of short-wave solar radiation, and balancing this inflow is an equivalent amount of energy returned to space as long-wave terrestrial radiation. The concept is a useful one, but it applies only to the earth as a whole, over an extended time scale of several years; it is not applicable to any specific area over a short period of time. This balance between incoming and outgoing radiation is referred to as the earth's energy budget.

The earth intercepts only a small proportion of the total energy given out by the sun—perhaps as little as one five-billionth (Critchfield 1983)—and not all of that reaches the earth's surface. The estimates differ in detail, but it is generally accepted that only about 50 per cent of the solar radiation arriving at the outer edge of the atmosphere is absorbed at the surface (Lutgens and Tarbuck 1982). That proportion is split almost equally between direct solar radiation and diffuse radiation, which has been scattered by water vapour, dust and other aerosols in its passage through the atmosphere (see Figure 2.5). Of the other 50 per cent, some 30 per cent returns to space as a result of reflection from the land and sea, reflection from clouds or scattering by atmospheric aerosols.

*Figure 2.5* The earth's energy budget



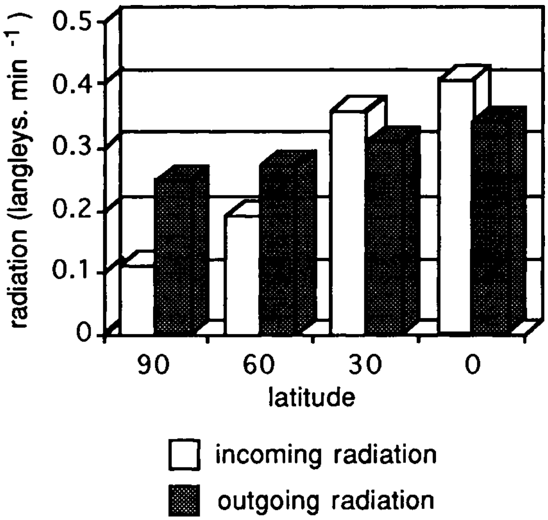

This 30 per cent of incoming radiation bounced back unaltered into space is a measure of the earth's reflectivity or albedo. The remaining 20 per cent of the original incoming radiation is absorbed mainly by oxygen, ozone and water vapour in the atmosphere. Thus, of every 100 units of solar energy arriving at the outer edge of the atmosphere, 70 are absorbed into the earth/ atmosphere system and 30 are returned to space having made no contribution to the system. Most of the 50 units absorbed by the earth are reradiated as long-wave, terrestrial radiation. Some energy is also transferred into the atmosphere by convective and evaporative processes at the earth's surface. The greenhouse gases trap the bulk of the outgoing terrestrial energy, but the atmosphere is transparent to wavelengths between 8 μm and 11 μm, and this allows 5 units of radiation to escape directly to space through the so-called atmospheric window. Some of the terrestrial radiation absorbed by the atmosphere is emitted to space also, but sufficient accumulates to allow 95 units to be reradiated back to the surface. The exchange of energy between the atmosphere and the earth's surface involves amounts apparently in excess of that provided by solar radiation. This is a direct function of the greenhouse effect, and its ability to retain energy in the lower atmosphere. Eventually all of the long-wave radiation passes out into space also, but not before it has provided the energy

*Table* 2.2 Estimated impacts of different radiative forcing agents in watts per square metre (1990–2000)

| *Forcing agents* | *Radiative forcing* ($Wm^{-2}$) | *Comments* |
|---|---|---|
| Greenhouse gases | +0.56<br>+0.41 | Business-as-usual<br>Major emission controls |
| Solar variability | +0.1<br>−0.1 | e.g. orbital changes and changes in solar irradiance – sunspot cycles |
| Large volcanic eruption | −0.2 | e.g. El Chichón, Mt Pinatubo |
| Anthropogenic sulphur emissions | +0.15?<br>−0.15? | Difficult to estimate – total emissions are declining, regional differences remain |
| Stratospheric $H_2O$ | +0.02 | |

*Source:* Based on data in Shine *et al.* (1990)

*Figure* 2.6 The latitudinal imbalance in solar and terrestrial radiation




necessary to allow the various atmospheric and terrestrial processes to function.

The energy balance of the earth/atmosphere system is subject to stress from both natural and anthropogenic sources. Any factor capable of disturbing that balance is called a radiative forcing agent (Shine *et al.* 1990). In the past, the most common sources of forcing were natural and involved changes in such elements as solar radiation, the planetary albedo and atmospheric aerosol concentrations, which individually and in combination altered the flow of energy into and out of the system. These natural forcing agents, continue to disrupt the balance, but current concern is with anthropogenic forcing agents and the climate change that they are likely to produce.

The depletion of the ozone layer resulting from human interference disturbs the balance by allowing additional radiation to reach the surface, and changes in atmospheric turbidity disrupt both incoming and outgoing radiation. In the immediate future, however, the greatest change in radiative forcing is expected to come about as a result of the rising levels of greenhouse gases (see Table 2.2). It is estimated that their effect on the radiative balance of the earth radiative forcing agent, natural or anthropogenic (Shine *et al.* 1990).

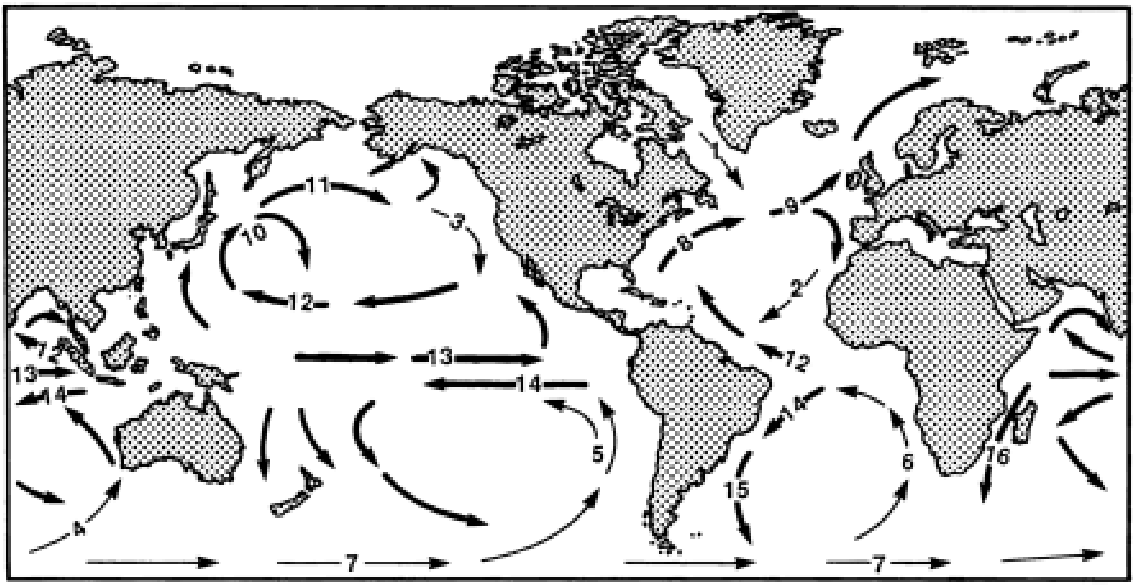
The concept of balance in the earth's heat budget is a useful one, but it provides only a global picture, and cannot be applied to specific areas. There is a definite latitudinal imbalance in the budget. Annually, the equator receives about five times the amount of solar radiation reaching the poles, and those areas equatorwards of 35 degrees of latitude receive more energy than is returned to space (Figure 2.6). The excess of outgoing radiation over incoming, poleward of 35 degrees of latitude, creates a radiation deficit in higher latitudes (Trewartha and Horn 1980). In theory, such an imbalance could lead to higher latitudes becoming infinitely colder and equatorial latitudes infinitely warmer. In reality, as soon as the latitudinal differences develop, they initiate circulation patterns in the atmosphere and in the oceans, which combine to transfer heat from the tropics towards the poles, and in so doing serve to counteract the imbalance.

## OCEANIC AND ATMOSPHERIC CIRCULATION PATTERNS

### The circulation of the oceans

More than half of the solar radiation reaching the earth's surface is absorbed by the oceans, where it is stored and redistributed, before being released back into the atmosphere. Ocean and atmosphere are quite intimately linked. The prevailing winds in the atmospheric circulation, for example, drive water across the ocean surface at speeds of less than 5 km per hour, in the form of broad, relatively shallow drifts. In some cases, they carry warm water polewards, in others, they carry cooler water into lower latitudes (see Figure 2.7). In addition, density differences, in part thermally induced, cause horizontal and vertical movement of water within the oceans. All of these processes help to transfer excess heat from equatorial regions towards the poles. This is illustrated particularly well in the North Atlantic, where the warm waters of the Gulf Stream Drift ensure that areas as far north as the Arctic Circle are anomalously mild during the winter months. The amount and rate of energy transfer varied in the past, producing significant climatological effects. Changes in the North Atlantic circulation, for example, may have contributed to the Ice Ages. Current estimates of poleward energy transfer in the northern hemisphere indicate that ocean transfer exceeds atmospheric transfer in

*Figure 2.7* The circulation of the oceans



COLD CURRENTS

1 Labrador
2 Canary
3 California
4 West Australia
5 Humboldt
6 Benguela
7 West Wind Drift

WARM CURRENTS

8 Gulf Stream
9 N. Atlantic Drift
10 Kuroshio
11 N. Pacific Drift
12 N. Equatorial
13 Equatorial Counter
14 S. Equatorial
15 Brazil
16 Agulhas

*Table 2.3* El Niño events of various intensities by century: 1525–1987

| Century | M–VS | M+–VS | S–VS | S+ | VS |
|---|---|---|---|---|---|
| 1525–99 | 19 | 15 | 10 | 1 | 1 |
| 1600–99 | 18 | 17 | 13 | 3 | 0 |
| 1700–99 | 22 | 17 | 11 | 2 | 3 |
| 1800–99 | 32 | 20 | 10 | 4 | 3 |
| 1900–87 | 24 | 15 | 8 | 0 | 2 |
| Total | 115 | 84 | 52 | 10 | 9 |

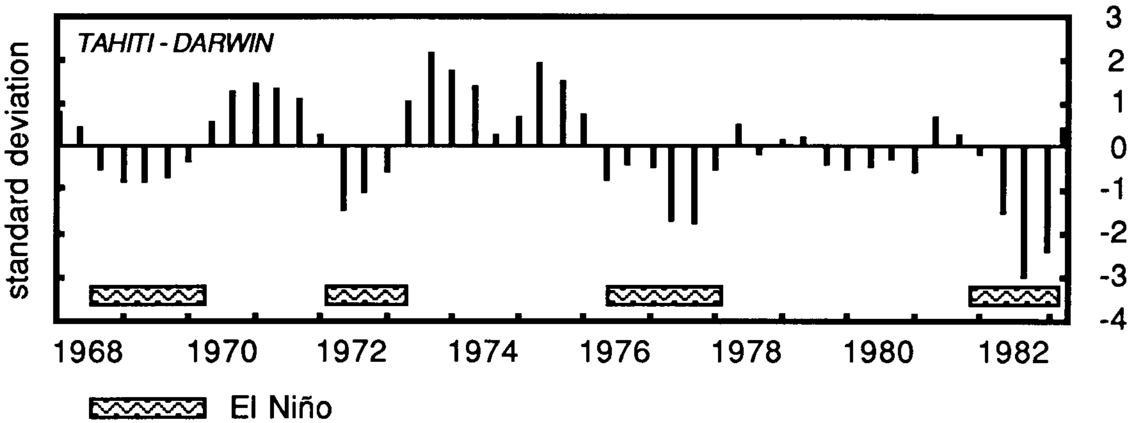
*Source:* Quinn and Neal (1992), p. 637
*Notes:* M=moderate; S=strong; VS=very strong; M+ = significantly exceeding the general characteristics of M; S+= significantly exceeding the general characteristics of S.

low latitudes, whereas the latter is more important in mid to high latitudes. On average, oceanic transport accounts for 40 per cent of the total energy transfer and atmospheric transport for 60 per cent (Trewartha and Horn 1980).

One ocean current which does not appear as part of the well-established pattern illustrated in Figure 2.7, but which makes a major contribution to energy transfer is El Niño. This is a flow of anomalously warm surface water which has appeared with some frequency over the centuries in the equatorial regions of the eastern Pacific (see Table 2.3). The name originally referred to a warm current which appeared off the coast of Peru close to Christmas—hence El Niño, the (Christ) Child—but now it is applied to a larger scale phenomenon (Lockwood 1984). It owes its development to the Southern Oscillation, a periodic fluctuation in atmospheric pressure in the southern Pacific, first recognized in the 1920s by Sir Gilbert Walker as he sought to develop methods for forecasting rainfall in the Indian monsoon. The term ENSO is commonly used to refer to the combination of El Niño and the Southern Oscillation.

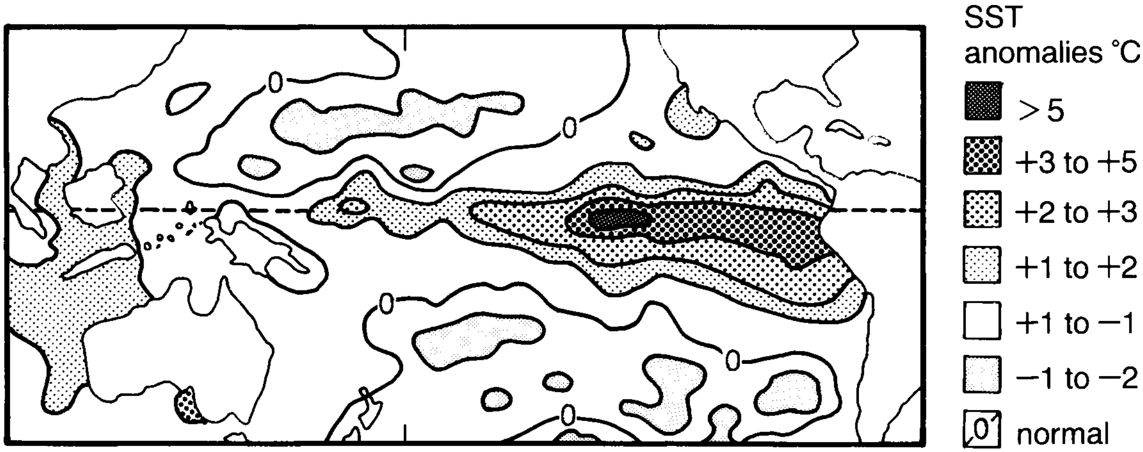
An indication of the Southern Oscillation is obtained by comparing barometric pressure differences between Tahiti, in the eastern Pacific, and Darwin, in northern Australia. Pressure at these two stations is negatively correlated, high pressure over Tahiti normally being accompanied by low pressure over Darwin, for example. In contrast, low pressure at Tahiti is matched by high pressure at Darwin. These pressure differences induce a strong latitudinal circulation in the equatorial atmosphere—referred to as the Walker circulation. Periodically the regional pressure patterns reverse and it is this phenomenon which is referred to as the Southern Oscillation

*Figure 2.8* The Southern Oscillation as represented by the Tahiti minus Darwin atmosphere pressure anomaly: 1968–82




*Source:* Adapted from Rasmusson and Hall (1983)

*Figure 2.9* Sea surface temperature (SST) anomalies in the Pacific Ocean: December 1982




*Source:* After Rasmusson and Hall (1983)

(see Figure 2.8). It has a periodicity of one to five years, and in its wake it brings changes in wind fields, sea surface temperatures and ocean circulation patterns. When pressure is high over Tahiti and low over Darwin, the general wind and surface water flow is from east to west, and there is a tendency for relatively warm water to pond up at the western end of the Pacific Ocean. The removal of the warm surface water from the eastern Pacific allows the upwelling of relatively cold water from below in that area. These conditions are reversed following the Oscillation. Easterly winds are replaced by the westerlies, as the atmospheric pressure changes, and warm water begins to flow east again to replace the cold (see Figure 2.9). It is this phenomenon which has come to be called El Niño. When it is strongly developed, it may keep areas in the eastern Pacific warmer than normal for periods of up to a year (Rasmusson and Hall 1983), but its influence extends far beyond the immediate area (see Chapter 3).

During some years—when the difference between the high pressure over Tahiti and low pressure over Darwin is particularly well-marked, for example—the equatorial easterly winds are stronger than normal, and push the cold water upwelling off the South American coast far across the Pacific. This creates a cold current, flowing east to west, which has been given the name La Niña. Like El Niño, it appears to have an effect outside the region, but as a recently identified phenomenon (1986), its full climatological significance is as yet uncertain (Hidore and Oliver 1993).

In addition to its direct role in energy transfer, the oceanic circulation also contributes to the earth's climate through its participation in the global carbon cycle. The oceans contain close to 80 per cent of the earth's total carbon at any one time. It is held in active storage, and is transferred between the oceanic and atmospheric reservoirs in the form of carbon dioxide. Horizontal and vertical mixing within the oceans helps to control the rate of that exchange, which impacts on the greenhouse effect and therefore on the earth's energy budget (Taylor 1992).

## The circulation of the atmosphere

George Hadley developed the classic model of the general circulation of the atmosphere some 250 years ago. It was a simple convective system,

*Figure 2.10a* Simple convective circulation on a uniform, non-rotating earth, heated at the equator and cooled at the poles

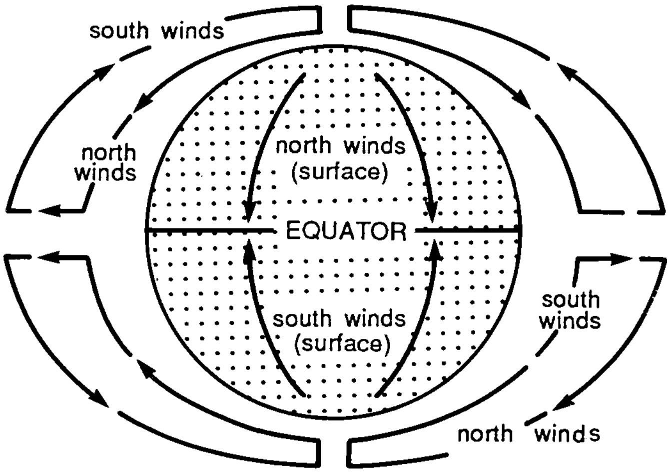
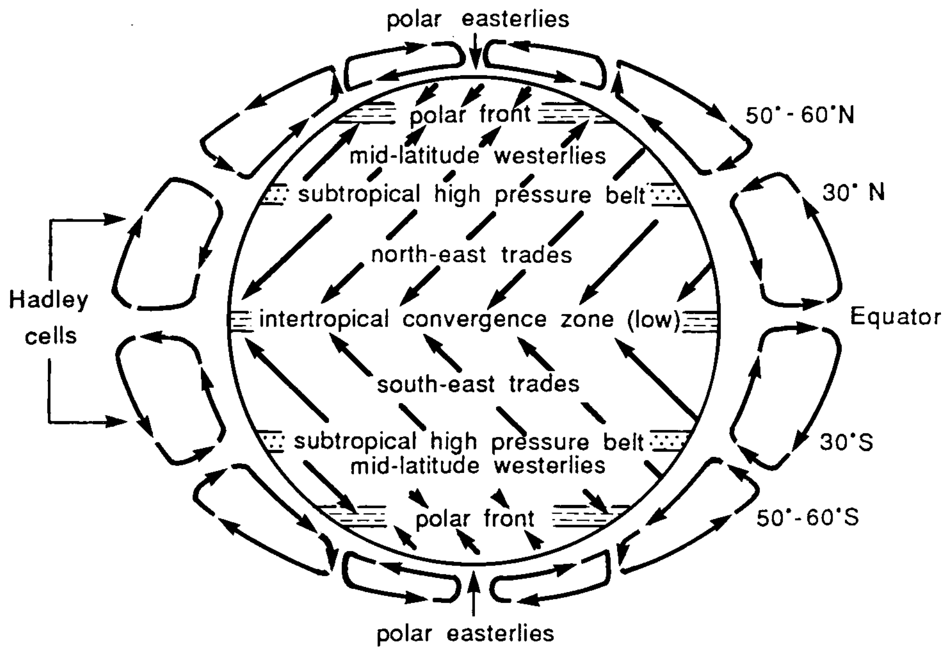


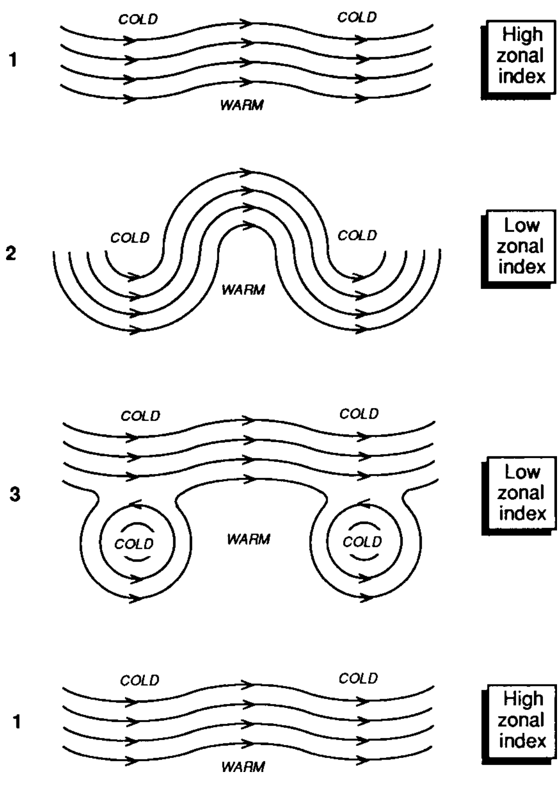

*Figure 2.10b* Three-cell model of the atmospheric circulation on a uniform, rotating earth, heated at the equator and cooled at the poles



based on the concept of a non-rotating earth with a uniform surface, which was warm at the equator and cold at the poles (see Figure 2.10a). The warmth caused the surface equatorial air to become buoyant and rise vertically into the atmosphere. As it rose away from its source of heat, it cooled and became less buoyant, but was unable to sink back to the surface because of the warm air rising behind it. Instead, it spread north and south away from the equator, eventually returning to the surface at the poles. From there it flowed back towards the equator to close the circulation. The air rising at the equator and spreading polewards carried energy with it, helping to reduce the energy imbalance between the equator and the poles. This type of energy transfer, initiated by differential heating, is called convection, and the closed circulation which results is a convection cell. Hadley's original model, with its single convection cell in each hemisphere, was eventually replaced by a three-cell model as technology advanced and additional information became available, but his contribution was recognized in the naming of the tropical cell (see Figure 2.10b). The three-cell model, continued to assume a uniform surface, but the rotation of the earth was introduced, and with it, the Coriolis effect, which causes moving objects to swing to the right in the northern hemisphere, and to the left in the southern. Thus, the winds became westerly or easterly in this new model, rather than blowing north or south as in the one cell version. The three cells and the Coriolis effect, in combination, produced alternating bands of high and low pressure, separated by wind belts which were easterly in equatorial and polar regions, and westerly in mid-latitudes. Although only theoretical, elements of this model can be recognized in existing global wind and pressure patterns, particularly in the southern hemisphere, where the greater expanse of ocean more closely resembles the uniform surface of the model.

In the late 1940s and 1950s, as knowledge of the workings of the atmosphere improved, it became increasingly evident that the three-cell model oversimplified the general circulation. The main problems arose with the mid-latitude cell. According to the model, the upper airflow in mid-latitudes should have been easterly, but observations indicated that it was predominantly westerly. The winds followed a circular path centred on the pole, which led to their description as circumpolar westerlies. Observations also indicated that most energy transfer in mid-latitudes was accomplished by horizontal cells rather than the vertical cell indicated by the model. The mechanisms involved included travelling high and low pressure systems at the surface plus wave patterns in the upper atmosphere called Rossby waves (Starr 1956). Modern interpretations of the general circulation of the atmosphere retain the tropical Hadley cell, but horizontal eddies

*Figure 2.11* The index cycle associated with the meandering of the mid-latitude westerlies in the northern hemisphere



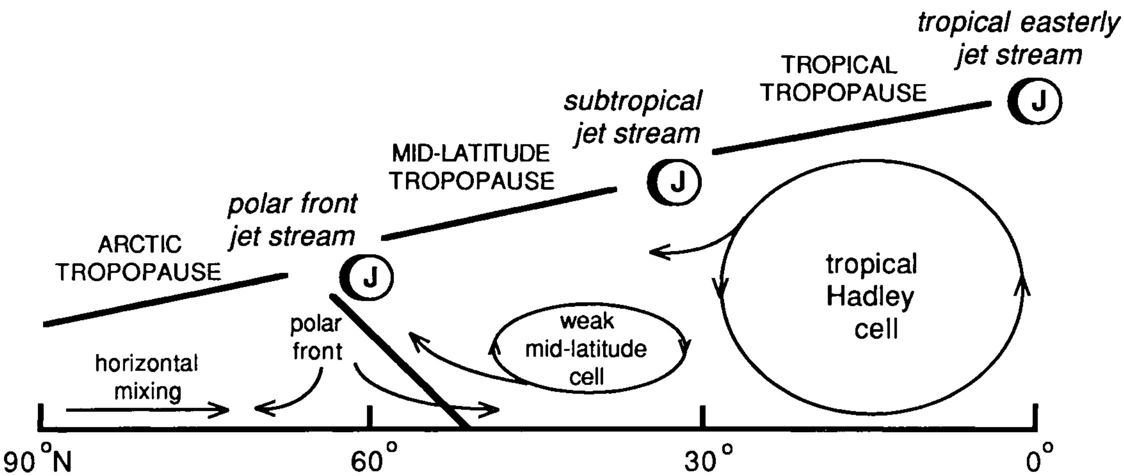
have come to dominate mid latitudes, and have even replaced the simple thermal cell of polar latitudes (Barry and Chorley 1992).

The flow pattern adopted by the Rossby waves is quite variable, and that variability makes a major contribution to energy transfer. When the westerlies follow a latitudinal path, from west to east they are said to be zonal, and the strength of the latitudinal flow is indicated by the zonal index. If the westerly flow is strong, the zonal index is high. In contrast, as the amplitude of the Rossby waves increases, the flow becomes less zonal and more meridional (i.e. it follows a north-south or longitudinal path). The zonal index is then said to be low. Changes in the wave patterns occur as indicated in Figure 2.11 and the entire sequence from high-zonal index, through low-zonal index and back to high is called the index cycle. It has an important role in the atmospheric energy exchange process. As the amplitude of the Rossby waves increases, and the westerlies loop southwards, they carry cold air into lower latitudes. Conversely, as they loop northwards they introduce warmer air into higher latitudes. These loops are often short-circuited, leaving pools of abnormally cool air in lower latitudes and abnormally warm air in high latitudes. The net result is significant latitudinal energy transfer. Such developments are not completely random, but neither are they predictable. The cycle occurs over a period of 3 to 8 weeks, and is repeated with some frequency, yet it lacks the regularity necessary for forecasting.

## The jet streams

The modification of the three-cell model in the 1940s and 1950s was made possible in large part by improved knowledge of conditions in the upper atmosphere. The upper atmospheric circulation is quite complex in detail, but in general terms it is characterized by an easterly flow in the tropics and a westerly flow associated with the Rossby waves in mid to high latitudes. Within these broad airflows, there are relatively narrow bands of rapidly moving air called jet streams, in which wind speeds average 125–130 km per hour in places. The jet streams are usually located at the tropopause, and are associated with zones in which steep temperature gradients exist, and where, in consequence, the pressure gradient is also steep. The most persistent jets are found in the sub-

*Figure 2.12* Schematic diagram of the vertical circulation of the atmosphere and the location of the major jet streams in the northern hemisphere



tropics, at the poleward edge of the tropical Hadley cell, and in mid-latitudes at the polar front (see Figure 2.12). Both of these jets generally flow from west to east. In addition, an Arctic jet, associated with the long polar night, has been identified (Hare and Thomas 1979), and an intermittent, but recognizable, easterly jet is a feature of the upper atmospheric circulation in equatorial regions (Barry and Chorley 1992).

The northern hemisphere polar front jet stream, the one most commonly encountered as headwinds or tail winds during trans-continental or trans-oceanic flights, is the best known of all the jet streams. It circles the earth in midlatitudes, following a meandering track from west to east at speeds averaging perhaps 100 km per hour, but with a maximum recorded speed of almost 500 km per hour (Eagleman 1985). During the winter, it follows a more southerly track, close to 35°N, and has an average velocity of 130 km per hour, whereas in the summer it is located closer to 50°N, and its velocity decreases to about 65 km per hour.

The influence of the polar front jet extends to the lower atmosphere, through its control over the various systems which produce the surface weather conditions. For example, the difference between a mild winter and a cold one, in the interior of North America, is often determined by the location of the polar front jet stream. A more southerly track allows the cold, polar air on the north side of the jet to penetrate into lower latitudes, whereas a more northerly track allows the continent to remain bathed in the warmer, southern air. The jet also exerts its influence on moisture regimes—through its control over the tracks followed by mid-latitude low pressure systems—and it has been implicated in the tornado outbreaks which occur in North America every spring. North-south thermal contrasts are strong, at that time, and the jet is therefore particularly vigorous (Eagleman 1985).

The importance of the jet stream and the associated upper westerlies, from an environmental point of view, lies in their ability to transport pollutants over great distances through the upper atmosphere. Smoke, volcanic debris and acid particles are all spread by such transportation, and, as a result, the problems they represent are global in scale. When above-ground atomic tests were being carried out in the USSR and China, during the 1950s and early 1960s, radioactive fallout was carried over northern Canada in the jet stream (Hare 1973). A similar mechanism spread the products of the Chernobyl nuclear accident. Any future nuclear war would cause great quantities of debris to be thrown into the upper atmosphere, where the jet streams would ensure a hemispheric distribution, and contribute to the rapid onset of nuclear winter.

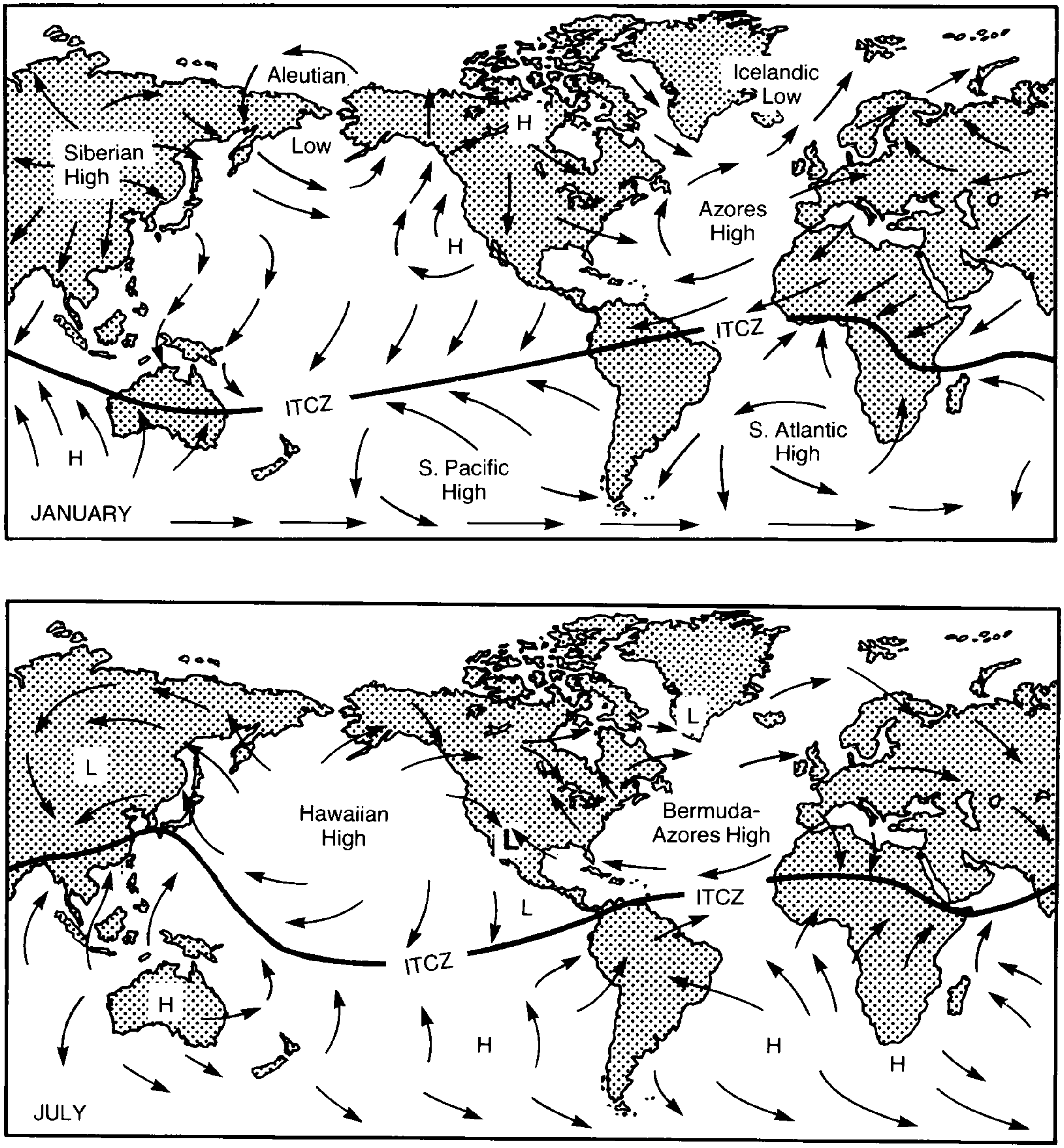
## The effects of surface conditions and seasonal variations

Modern representations of the general circulation of the atmosphere take into account the non-uniform nature of the earth's surface, with its mixture of land and water, and include consideration of seasonal variations in energy flow (see Figure 2.13).

Land and water respond differently to the same energy inputs, because of differences in their physical properties. Land tends to heat up and cool down more rapidly than water, and temperatures over land exhibit a greater range, diurnally and seasonally, than those over water. These temperature differences in turn have an impact on atmospheric pressure, particularly in the northern hemisphere with its juxtaposition of oceans and major land masses. During the northern summer, for example, higher temperatures promote lower pressure over the continents, whereas the adjacent seas are cooler, and pressure remains high in the cells which represent the sub-tropical high pressure belt over the North Atlantic and Pacific oceans. By altering the regional airflow, such pressure differences cause disruption of the theoretical global circulation patterns.

The permanent or semi-permanent features of the circulation also vary in extent and intensity,

*Figure 2.13* Global wind and pressure patterns for January and July




by the season or by the year, and in some cases over much shorter time scales as patterns of energy flow change. There is a general southward shift of the systems during the northern winter, for example. The Intertropical Convergence Zone (ITCZ)—the belt of low pressure produced by the combination of equatorial heating and the convergence of trade winds—migrates southwards in sympathy with the southward movement of the zone of maximum energy receipt. Behind it, the sub-tropical anticyclones also move south, contracting as they do so, allowing the mid-latitude westerlies and their associated travelling highs and lows to extend their influence into lower latitudes.

In the southern hemisphere at this time, the sub-tropical high pressure systems expand, and extend polewards over the oceans. The increased solar radiation of the summer season contributes to the formation of thermal lows over South America, Africa and Australia. The absence of major landmasses polewards of 45–50°S allows the westerly wind belt to stretch as a continuous band around the earth.

The patterns change during the northern summer, as the ITCZ moves northwards again, and the other elements of the system respond to changing regional energy budgets. Although such changes are repeated year after year, the movements of the systems are not completely reliable. In the tropics, for example, the ITCZ migrates at different rates and over different distances from one year to the next. This inherent variability contributes to the problem of drought. It also adds complexity to the impact of environmental problems—such as the enhanced greenhouse effect or atmospheric turbidity—which cause changes in the earth's energy budget, and therefore have the potential to alter circulation patterns.

## AUTOVARIATIONS AND FEEDBACK

It is convenient to consider the various elements of the earth/atmosphere system as separate entities, as has been done here. They are, however, quite intimately linked, and understanding the nature of these links is important—not only in the pure scientific study of the atmosphere itself, but also in the applied, interdisciplinary approach required for the study of modern global environmental problems. The elements and processes incorporated in the earth's energy budget and the atmospheric circulation, for example, are parts of a dynamic system, in which the components are sufficiently integrated that one change will automatically produce others. Such changes, produced through the activities of internal processes are called autovariations (Trewartha and Horn 1980), and, in combination with feedback mechanisms, they may augment or dampen the effects of a particular change in the system. Lower temperatures at the earth's surface, for example, would allow the persistence of snow cover beyond the normal season. This, in turn, would increase the amount of solar radiation reflected back into space, causing surface temperatures to fall even more, and encourage the snow to remain even longer. Such a progression, in which the original impact is magnified, illustrates the concept of positive feedback. Rising temperatures may initiate negative feedback. One of the initial effects of higher temperatures would be an increase in the rate of evaporation from the earth's surface. Subsequent condensation of the water vapour in the atmosphere, would increase cloudiness, and reduce the amount of solar radiation reaching the surface. As a result, temperatures would fall again, and the initial impact of rising temperatures would be diminished. Ultimately, these changes in the earth's energy budget would be reflected in the general circulation of the atmosphere. Many current global issues—such as the intensification of the greenhouse effect, increased atmospheric turbidity and desertification—involve autovariations, and include positive or negative feedback in their development.

## MODELLING THE ATMOSPHERE

Atmospheric modelling has a long tradition in climatology, stretching back to Hadley and his basic representation of the earth's wind and pressure belts. That classic model of the atmospheric circulation, along with the many variants which were subsequently developed, was a representative model. It showed the characteristic distribution of wind and pressure across the earth's surface in a simplified form, with no attempt to predict change in the system. Change was first dealt with at the local or regional level when attempts were made to forecast future weather conditions, and it is to weather forecasting that most modern predictive models can trace their origins. The earliest weather forecasts depended very much on the interpretation of atmospheric conditions by an experienced observer who used his accumulated knowledge of past events to predict future short-term changes in weather conditions. Particular skills in that field were often attributed to sailors, farmers and others who were regularly exposed to the vagaries of the weather in their work. This subjective approach continued well into modern times, but by the end of World War I the first of the modern predictive models was being developed. This was the mid-latitude frontal model which grew out of the work of the Norwegian school of meteorology. With its combination of air masses, anticyclones and frontal depressions it was the mainstay of weather forecasting in mid-latitudes for half a century. Past experience with such systems coupled with observations of their on-going development allowed local weather conditions to be predicted twelve to twenty-four hours ahead. As knowledge of the working of the atmosphere grew in the 1940s and 1950s, it became clear that such models over-simplified the complex dynamics of the atmospheric system, and new methods of prediction were sought.

In these new models, atmospheric physical processes were represented by a series of fundamental equations. Three of the equations were derived from the laws of conservation of momentum, mass and energy, which dealt with motion in the atmosphere. In addition, the models included an equation of state derived from the gas laws of classical physics—which related atmospheric pressure, density and temperature—plus a moisture equation (Washington and Parkinson 1986). When solved repeatedly for a series of small but incremental changes, at selected grid points across the study area, these equations provided a forecast of the future state of the atmosphere. L.F.Richardson, a British meteorologist, was a pioneer in this field, publishing the results of his work in 1922 in his book, *Weather Prediction by Numerical Process* (Ashford 1981). At that time his methods were not practicable. The complexity of the computations, and the existence of only rudimentary methods of mechanical calculation meant that the predictions could not keep ahead of changing weather conditions. As a result no real forecast could be made. The inadequacies of existing upper-air observations also contributed to the failure of this first attempt at numerical forecasting (Ashford 1992).

Following this initial setback, little was done to develop numerical prediction further until the 1950s and 1960s when advances in computer technology and improved methods of observation led to the development of models capable of predicting changes in the essential meteorological elements across the globe. Since then these methods have been widely adopted, and numerical modelling is currently the most common method of weather forecasting for periods of several hours to 5 or 6 days ahead. Problems remain, however, despite the growing sophistication of the systems used. Gaps exist in the data required to run the models, for example. Ocean coverage is thin and the number of observing stations in high latitudes is small. Problems of scale may also arise depending upon the horizontal and vertical resolution of the model. A coarse resolution, for example, will miss the development of small scale phenomena such as the shower cells associated with local convective activity. A fine resolution model will provide greater accuracy, but only at a cost. Even the simplest weather models require a billion mathematical operations before they can produce a single day's forecast (Levenson 1989). In setting up the grid reference points used in the calculations, therefore, a compromise has to be struck between the accuracy required and the cost of running the program. The UK Meteorological Office, for example has developed two variants of its forecasting model. The global version has a horizontal grid with a resolution of 1.5° latitude by 1.875° longitude, and includes fifteen levels stretching from the surface into the stratosphere. In contrast, a finer grid with a resolution of 0.75° latitude and 0.9375° longitude is only available for an area covering the North Atlantic and Western Europe (Barry and Chorley 1992).

Atmospheric models designed to simulate climate change also depend upon numerical prediction, but they differ in a number of important ways from the weather forecasting models. For example, over the short time periods (4–5 days) covered by the weather forecasting models, environmental elements such as vegetation, oceans, ice sheets and glaciers can be considered as static or unchanging, and therefore contributing little to atmospheric change. Over the longer time scales (10–50 years) involved in in the climate models, however, these elements would be expected to change, and that change must be incorporated in the models. This may be simple if the change remains linear, but difficulties arise when response to change initiates feedback in the earth/atmosphere system. Many of the uncertainties in the results of climate modelling can be traced to the inability of the models to deal adequately with climate feedback mechanisms.

The spatial resolution of climate models also tends to be coarser than that of weather models. Modern computer systems are remarkably sophisticated, but their use is at times constrained by such factors as operational speed, memory capacity and cost. For example, the additional calculations introduced to accommodate the longer time scale and greater number of environmental variables incorporated in the climate models increases the computer memory and time required. This in turn increases the cost of running the model. A reduction in the number of grid points at which the calculations are made helps to keep these elements at manageable levels, but it also produces a coarser resolution in the model. Typical climate models have a resolution which is three to six times coarser than that of weather forecasting models. Although this still allows adequate representation of macro-scale climate features, it gives only limited results at the regional level (Cubasch and Cess 1990). In an attempt to improve regional or meso-scale resolution, Australian scientists have developed a method in which a meso-scale model is 'nested' or 'embedded' within a macro-scale global climate model. This nested model, driven by the global model which surrounds it, is programmed to provide much finer detail at the regional level than is possible with the standard model alone. Since the extra information is required for only a limited area, and the running of the global model is unaffected, both the additional computer time needed and the costs remain manageable. Tests suggest that this is the best method currently available for achieving increased spatial resolution, although it requires further development before it can be used for climate prediction (Henderson-Sellers 1991).

Several important climatic processes take place at regional scales, and are therefore missed by the macro-scale grids of most climate models. However, since they affect the predictions produced by the models, they must be included. This is done through a process of parameterization, in which statistical relationships are established between the small scale processes and the grid scale variables. Since the latter can be calculated by the models, the values of the small scale processes can then be estimated (Hengeveld 1991). For example, existing models cannot deal with individual clouds, but average cloudiness in a particular grid-box can be predicted using temperature and humidity values calculated by the model (Schneider 1987). Other variables that require parameterization include radiation, evaporation and land surface processes.

Climate models take various forms, and involve various levels of complexity, depending upon the application for which they are designed. A simple model, for example, may provide only one value, such as the average temperature of the earth. Increasing levels of sophistication produce one- and two-dimensional models and the complex three-dimensional general circulation models, which depend upon the full use of numerical prediction to produce results.

One dimensional (1-D) models provide information on change along a vertical line stretching from the earth's surface up into the atmosphere. The main inputs into these models are incoming solar radiation and returning terrestrial radiation, and they can be used to estimate such elements as temperature changes initiated by changing atmospheric aerosol levels. They treat the earth as a uniform surface with no geography and no seasons. As a result they are inadequate to deal with the uneven surface energy distribution associated with the differences in heat capacity between land and ocean. One dimensional models have been used frequently to estimate the impact of volcanic eruptions on climate, and a 1-D radiative convective model was used to establish the TTAPS scenario of nuclear winter (Turco *et al.* 1983). At best, 1-D models are useful for the preliminary investigation of global scale radiative and convective processes at different levels in the atmosphere. However, they cannot deal with seasonal or regional scale features, and require so many assumptions that their ability to provide accurate predictions is limited.

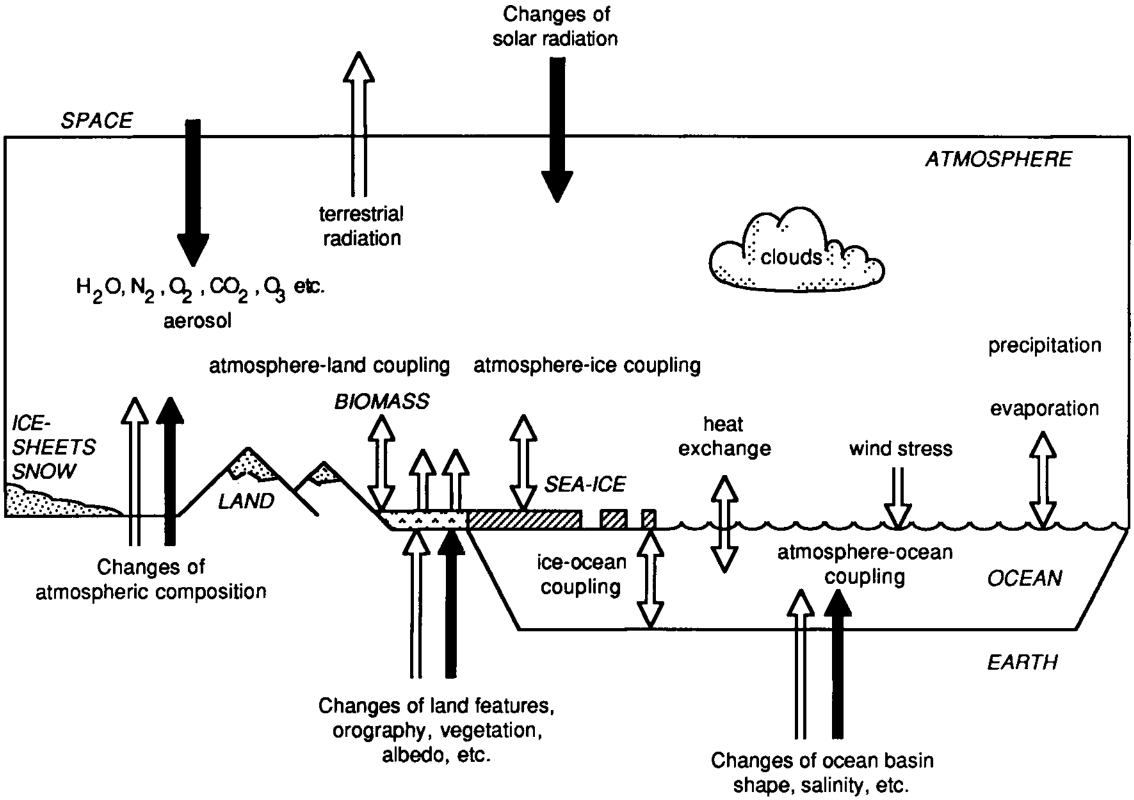
Two-dimensional (2-D) models add a meridional or latitudinal component to the altitudinal component of the 1-D models. They can consider variations in climate along a vertical cross-section from pole to pole, for example, or along a specific line of latitude. This allows the horizontal redistribution of such elements as energy or particulate matter to be examined. Two-dimensional models can therefore include consideration of differences in heat capacity between land and ocean, but their ability to deal with the evolving dynamics of the atmosphere once change has been initiated remains limited. Like the 1-D models, they contributed to the early development of the concept of nuclear winter, but they were quickly superseded by more sophisticated three-dimensional models.

Three-dimensional (3-D) models provide full spatial analysis of the atmosphere. They incorporate major atmospheric processes plus local climate features predicted through the process of parameterization. The simulations of current and future climates provided by these models require powerful computers capable of processing as many as 200,000 equations at tens of thousands of points in a three-dimensional grid covering the earth's surface, and reaching through two to fifteen levels as high as 30 km into the atmosphere (Hengeveld 1991). In addition to these grid-point models, spectral models have been developed. In these, the emphasis is on the representation of atmospheric disturbances or waves by a finite number of mathematical functions. Many of the more advanced models incorporate this approach (Cubasch and Cess 1990).

Climate models of this type are known as general circulation models (GCMs). They can be programmed to recognize the role of land and sea in the development of global climates. Their complex representation of atmospheric processes allows the inclusion of the important feedback mechanisms missing from 1-D and 2-D models, and they can deal with the progressive change set in motion when one or more of the components of the atmosphere is altered. With typical integration times for GCMs ranging from several decades to 100 years, this ability to deal with the evolving dynamics of the atmosphere is important.

In an attempt to emulate the integrated nature of the earth/atmosphere system, atmospheric GCMs have been coupled with other environmental models (see Figure 2.14). Recognizing the major contribution of the oceans to world climatology, the most common coupling is with ocean models. In theory, such models combining the atmospheric and oceanic circulations should provide a more accurate representation of the earth's climate. This is not always the case, however. The coupling of the models leads to the coupling of any errors included in the individual models. The so-called 'model drift' which occurs can be treated, but it remains a constraint for coupled models (Cubasch and Cess 1990). Another major problem is the difference in time scales over which atmospheric and oceanic phenomena develop and respond to change. The atmosphere generally responds within days, weeks or months, while parts of the oceans—the ocean deeps, for example—may

*Figure 2.14* Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change




*Source:* From Houghton *et al.* (1990)

take centuries or even millenia to respond (Washington and Parkinson 1986). As a result, running a completely interactive coupled atmosphere-ocean model, until all elements reach equilibrium, is time-consuming and costly. Because of this, the oceanic element in most coupled models is much less comprehensive than the atmospheric element. The ocean is commonly modelled as a slab which represents only the uppermost layer of water in which the temperature is relatively uniform with depth. Oceanic heat storage is calculated only for the chosen depth of the layer, and other elements such as oceanic heat transport and exchanges with the deeper parts of the ocean are neglected or calculated indirectly (Cubasch and Cess 1990). Thus, although the coupling of the atmospheric and oceanic circulations should improve the accuracy of the modelling process, since it more closely emulates the real environment, the results are often no better than those obtained from the individual uncoupled models (Washington and Parkinson 1986).

Sea-ice models, carbon cycle models and chemical models have also been recognized as having the potential to contribute to climate simulation when coupled to existing GCMs. Sea-ice has been incorporated in some ocean models, but separate sea-ice simulation models have also been created. Carbon cycle models,

*Table 2.4* Some commonly used general circulation models

| *Model/source* | **Resolution* | *Vertical layers* | *Ocean heat transport* | *Clouds* | *Cloud properties* |
|---|---|---|---|---|---|
| **1 Fixed zonally averaged cloud; no ocean heat transport** | | | | | |
| GFDL Geophysical Fluid Dynamics Laboratory, USA | R15 | 9 | Not included | Fixed cloud | Fixed cloud radiative properties |
| **2 Variable cloud; no ocean heat transport** | | | | | |
| OSU Oregon State University, USA | 4° × 5° | 2 | Not included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| MRI Meteorological Research Institute, Japan | 4° × 5° | 5 | Not included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| NCAR National Centre for Atmospheric Research, USA | R15 | 9 | Not included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| GFDL | R15 | 9 | Not included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| **3 Variable cloud; prescribed oceanic heat transport** | | | | | |
| AUS Commonwealth Scientific and Industrial Research Organization, Australia | R21 | 4 | Included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| GISS Goddard Institute of Space Sciences, USA | 8° × 10° | 7 | Included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| GFDL | R15 | 9 | Included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| MGO Main Geophysical Observatory, Russia | T21 | 9 | Included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| UKMO Meteorological Office, UK | 5° × 7.5° | 11 | Included | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| UKMO | 5° × 7.5° | 11 | Included | Cloud water | Variable cloud radiative properties |

*Table 2.4* continued

| *Model/source* | **Resolution* | *Vertical layers* | *Ocean heat transport* | *Clouds* | *Cloud properties* |
|---|---|---|---|---|---|
| **4 High resolution** | | | | | |
| CCC Canadian Climate Centre | T32 | 10 | Included | Condensation or relative humidity based cloud | Variable cloud radiative properties |
| GFDL | R30 | 9 | Sea surface temperatures prescribed | Condensation or relative humidity based cloud | Fixed cloud radiative properties |
| UKMO | 2.5° × 3.75° | 11 | Included | Cloud water | Fixed cloud radiative properties |

All models are global, with realistic geography, a mixed layer ocean, and a seasonal cycle of insolation

**5 Global coupled ocean-atmosphere models**

| | **Resolution* | *Vertical layers* | *Ocean layers* | *Cloud properties* |
|---|---|---|---|---|
| GFDL | R15 | 9 | 12 | Moist convective adjustment |
| NCAR | R15 | 9 | 4 | Fixed cloud radiative properties |
| MPI Max Planck Institut für Meteorologie, Germany | T21 | 19 | 11 | Cloud water |
| UHH Met. Institute, U. of Hamburg, Germany | T21 | 19 | 9 | Cloud water |

*Source:* Compiled from data in Cubasch and Cess (1990) All models are global, with realistic geography and a seasonal cycle of insolation
*Resolution is defined either by latitude and longitude (e.g. 4°×5°) in grid point models, or by the number of waves (moving disturbances) that can be accommodated in spectral models (e.g. R15 or T32).

particularly important in studies of global warming, have already been coupled to ocean models, and chemical models are being developed to investigate the influence of other trace gases on the general circulation of the atmosphere (Cubasch and Cess 1990).

Global circulation models are being developed or refined at about a dozen universities, government laboratories and research institutes around the world (see Table 2.4). Most of the effort has gone into producing equilibrium models. In these change is introduced into a model which represents existing climate conditions, and the model is then allowed to run until a new equilibrium is reached. The new model climate can then be compared with the original to establish the overall impact of the change, The numerous GCMs used to study the impact of a doubling of atmospheric carbon dioxide on world climates are of this type. They make no attempt to estimate changing conditions during the transient phase of the model run, although these conditions may well have important environmental impacts long before equilibrium is reached. The development of transient or time-dependent models which would provide the interim information currently lags behind that of the equilibrium models. The few existing transient models are of coarse resolution, but yield results which are broadly consistent with those from the more common equilibrium models (Bretherton *et al.* 1990). They incorporate a coupled ocean-atmosphere system with full ocean dynamics, and require increased computer power and improved ocean observation data, before they can make a greater contribution to the study of future climate change.

Despite the increasing complexity of current GCMs, the fact remains that like all models they represent a compromise between the complexities of the earth/atmosphere system and the constraints imposed by such factors as data availability, computer size and speed and the cost of model development and operation, which limit the accuracy of the final result. The quality of specific simulations can be tested by comparing model predictions with the results obtained by direct measurement or observation. This approach shows, for example, that GCMs can simulate short-term changes such as seasonal cycles remarkably well (Schneider 1987), and their portrayal of atmospheric responses to sea surface temperature anomalies is usually considered as satisfactory. Simulations of Holocene climates, which provide an indication of the long-term capabilities of the models, have given results supported by palaeo-environmental indicators, such as fossil pollen distribution and former lake levels, revealed in lake and ocean sediment cores (Gates *et al.* 1990). These tests indicate that most simulations can represent the large scale characteristics of climate quite well, but significant errors remain at regional scales as a result of the coarse resolution common to most models. The accuracy of coupled models is also restricted by inadequate data on which to base the oceanic component. More powerful computers and improved parameterization will take care of some of these problems, but the general consensus is that the gap between climate simulation and reality will remain for some time to come.

## SUMMARY

Changes in such elements as the composition of the atmosphere, global circulation patterns and the earth's energy budget are now widely recognized as components of most current global environmental issues. The relationships involved are complex, and remain imperfectly understood despite major advances in the acquisition and analysis of atmospheric data. Global climate models have been developed to investigate the processes further, and provide forecasts of future developments. These investigations and forecasts will allow a more effective response to the changes with the ultimate aim of minimizing their environmental impact.

## SUGGESTIONS FOR FURTHER READING

Ahrens, C.D. (1993) *Essentials of Meteorology,* Minneapolis/St Paul: West Publishing Company.

Barry, R.G. and Chorley, R.J. (1992) *Atmosphere, Weather and Climate,* London: Routledge.

Briggs, D., Smithson, P. and Ball, T. (1993) *Fundamentals of Physical Geography,* Mississauga, Ontario: Copp Clark Pitman.

Hidore, J.J. and Oliver, J.E. (1993) *Climatology: An Atmospheric Science,* New York: Macmillan.

Levenson, T. (1989) *Ice Time: Climate, Science and Life on Earth,* New York: Harper and Row.

# 3

# Drought, famine and desertification

In recent years, the world's attention has been drawn time and again to the Third World nations of Africa, by the plight of millions of people who are unable to provide themselves with food, water and the other necessities of life. The immediacy of television, with its disturbing images of dull-eyed, pot-bellied, malnourished children, skeletons of cattle in dried-up water courses, and desert sands relentlessly encroaching upon once productive land, raised public awareness to unexpected heights, culminating in the magnanimous response to the Live Aid concerts of 1985. Not unexpectedly, given the requirements of modern popular journalism and broadcasting, coverage of the situation has often been narrow, highly focused and shallow, lacking the broader, deeper investigation necessary to place the events in a geographical or environmental framework. For example, the present problems are often treated as a modern phenomenon, when, in fact, they are in many ways indigenous to the areas involved. The inhabitants of sub-Saharan Africa have suffered the effects of drought and famine for hundreds of years (see Table 3.1). It is part of the price that has to be paid for living in a potentially unstable environment.

*Table 3.1* Wet and dry spells in Africa south of the Sahara

| *Dry* | *Wet* |
|---|---|
| 1680s | 10th–13th centuries |
| 1740s | 1870s–mid-1890s |
| 1750s | 1920s–59 (mixed but mainly wetter) |
| Late-1790s–1800 | 1988–89 |
| 1820s | |
| 1830s | |
| 1895–1910s | |
| 1968–73 | |
| 1980s | |
| 1990 | |

*Source:* After Nicholson (1989)

Current episodes seem particularly catastrophic, but they are only the most recent in a continuing series. In dealing with the situation, the media have tended to concentrate on the problems of famine and its consequences, while most of the aid being supplied has, of necessity, been aimed at alleviating hunger. However, while famine may be the direct cause of the present suffering and hardship, it is, in reality, a symptom of more fundamental problems. Elements of a cultural, socio-economic and political nature may contribute to the intensity and duration of the famine, but, in areas such as the Sahel, the ultimate causes are to be found in the environmental problems associated with drought and desertification. The former, through its impact on plants and animals, destroys the food supply, and initiates the famine; the latter, with its associated environmental changes, causes the productive land to become barren, and ensures that the famine will persist, or at least recur with some frequency. Together, drought, famine and desertification have been implicated in some of the major human catastrophes of the past and present, and will undoubtedly contribute to future suffering and despair.

## DROUGHT

### The problem of definition

Drought is a rather imprecise term with both popular and technical usage. To some, it indicates a long, dry spell, usually associated with lack of precipitation, when crops shrivel and reservoirs shrink. To others, it is a complex combination of meteorological elements, expressed in some form of moisture index (see Table 3.2). There is no widely accepted definition of drought. It is, however, very much a human concept, and many current approaches to the study of drought deal with moisture deficiency in terms of its impact on human activities, particularly those involving agriculture. Agricultural drought is defined in terms of the retardation of crop growth or development by reduced soil moisture levels. This in turn may lead to economic definitions of drought when, for example, dry conditions reduce yield or cause crop failure, leading to a reduction in income. It is also possible to define drought in purely meteorological terms, where moisture deficiency is measured against normal or average conditions, which have been established through long-term observations, such as those illustrated in Figure 3.1 (Katz and Glantz 1977).

### Aridity and drought

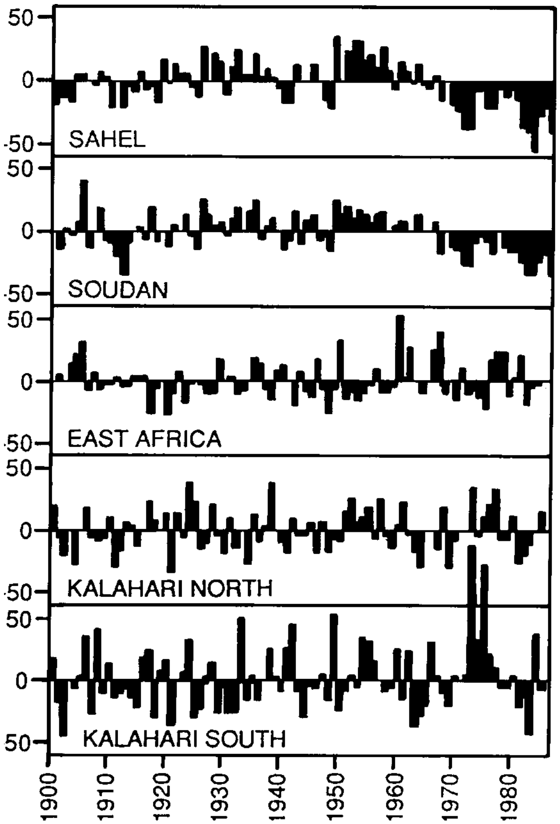
The establishment of normal moisture levels also allows a distinction to be made between aridity and drought. Aridity is usually considered to be

*Table 3.2* Examples of drought and aridity indices

| *Author* | *Name* | *Formula* |
|---|---|---|
| de Martonne (1926) | Index of aridity | $P/(T+10)$ |
| Thornthwaite | P/E Index | $P/E = \sum_{1}^{12} 1.65 \left(\frac{P_i}{t_i + 12.2}\right)^{0.9}$ |
| Capot-Rey (1951) | Improved Aridity Index | $A = \frac{1}{2}\left(\frac{P}{T+10} + \frac{12p_i}{t_i + 10}\right)$ |
| Palmer (1965) | Drought Severity Index | $x_i = \sum_{r-1}^{i} \frac{P - \hat{P}}{(\overline{PE} + \bar{R})/(\hat{P} + L)} \Big/ (ar+b)$ |

*Source:* After Landsberg (1986) *Symbols*
$P$ mean annual precipitation (mm)
$T$ mean annual temperature (°C)
$P_i$ individual monthly precipitation (mm)
$t_i$ individual monthly temperature (°C)
$\hat{P}$ climatically appropriate water balance for existing conditions
$\overline{PE}$ annual potential evapotranspiration
$L$ loss (mm)
$\bar{R}$ mean monthly recharge
$r$ number of months

*Figure 3.1* Rainfall fluctuations in five regions of Africa, 1901–87: expressed as a per cent departure from the long-term mean




*Source:* After Nicholson (1989)

the result of low average rainfall, and is a permanent feature of the climatology of a region (see Figure 3.2a). The deserts of the world, for example, are permanently arid, with rainfall amounts of less than 100 mm per year. In contrast, drought is a temporary feature, occurring when precipitation falls below normal or when near normal rainfall is made less effective by other weather conditions such as high temperature, low humidity and strong winds (Felch 1978).

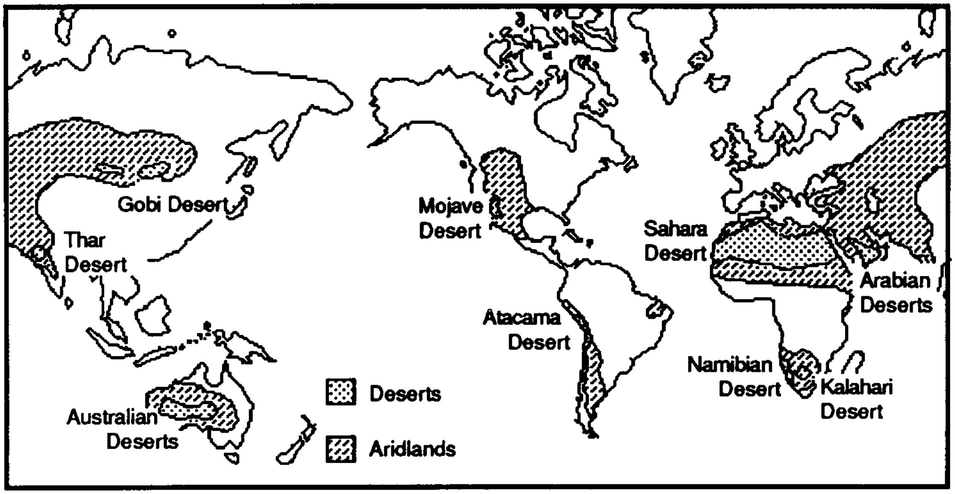
Aridity is not a prerequisite for drought. Even areas normally considered humid may suffer from time to time, but some of the worst droughts ever experienced have occurred in areas which include some degree of aridity in their climatological makeup. Along the desert margins in Africa, for example, annual precipitation is low, ranging between 100 and 400 mm, but, under normal conditions, this would allow sufficient vegetation growth to support pastoral agriculture. Some arable activity might also be possible, if dry-farming techniques were employed. Drought occurs with considerable regularity in these areas (Le Houerou 1977). The problem lies not in the small amount of precipitation, but rather in its variability. Mean values of 100 to 400 mm are based on long-term observations, and effectively mask totals in individual years, which may range well above or below the values quoted (see Figure 3.3). Weather records at Beijing, in drought-prone northern China, show that the city receives close to 600 mm of precipitation in an average year. However, the amount falling in the wetter years can be 6–9 times that of the drier years. Only 148 mm were recorded in 1891, for example, and 256 mm in 1921, compared to a maximum of 1,405 mm in 1956 (NCGCC 1990). Rainfall variability is now recognized as a major factor in the occurrence of drought (Oguntoyinbo 1986), and a number of writers have questioned the use of 'normal' values in such circumstances. In areas of major rainfall variability the nature of the environment reflects that variability rather than the so-called normal conditions, and any response to the problems which arise from drought conditions must take that into account (Katz and Glantz 1977).

Some researchers claim that the drought in sub-Saharan Africa has been intensifying as a result of climatic change. Bryson (1973), for example, has identified changes in atmospheric circulation patterns which could intensify and prolong drought in the Sahel. There is, however, no conclusive evidence that the current drought is anything other than a further indication of the inherent unreliability of precipitation in the area (Nicholson 1989).

## The human response to drought

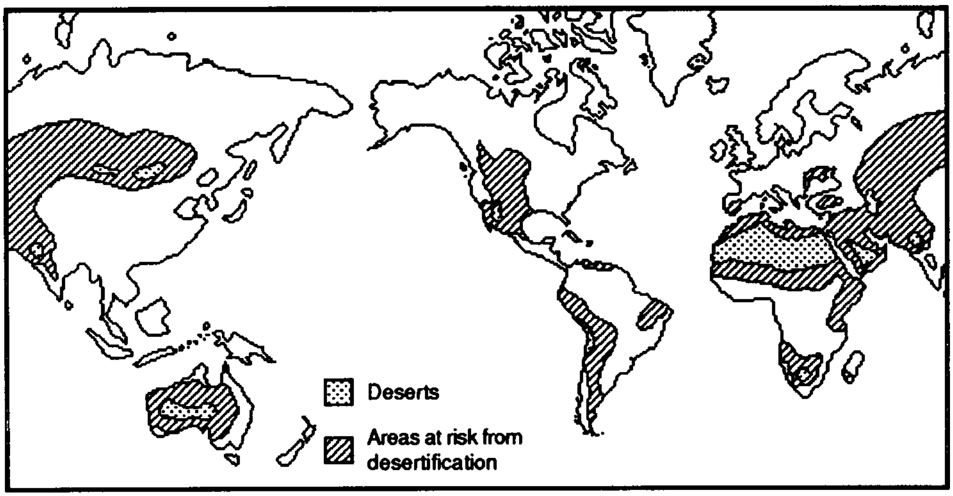
Each generation has its images of drought. In

*Figure 3.2a* The deserts and arid lands of the world




*Source:* Compiled from various sources

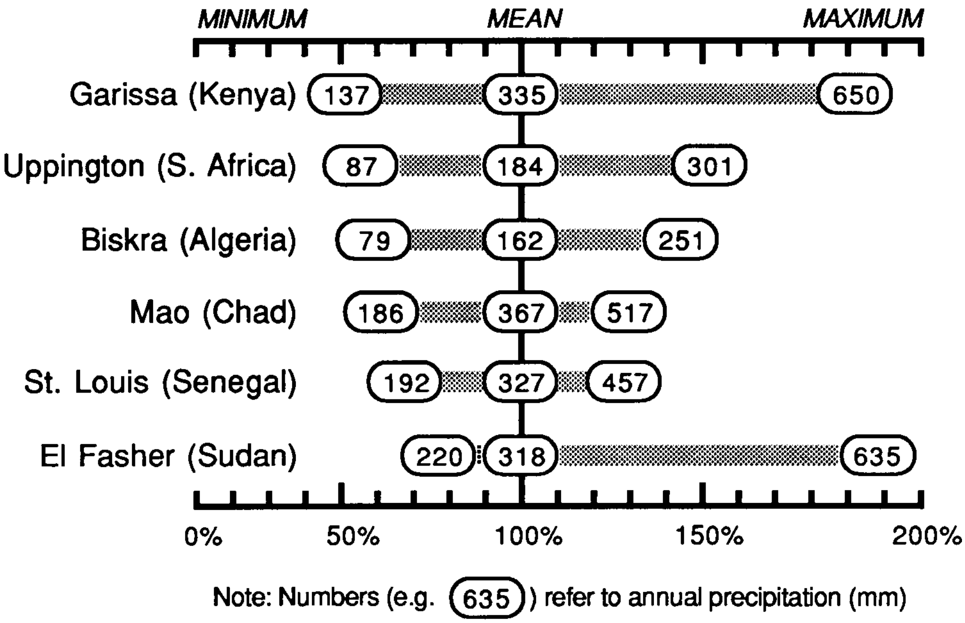
*Figure 3.2b* Areas at risk from desertification




*Source:* Compiled from various sources

the 1990s it is East Africa; in the 1980s it was Ethiopia; in the 1960s it was the Sahel; in the 1930s it was the Dustbowl, described with such feeling by John Steinbeck in *The Grapes of Wrath*. Although these have gripped the popular imagination, they are only the more serious examples of perhaps the most ubiquitous climatological problem that society has to face, Drought strikes areas as far apart as Australia and the Canadian Prairies, or southern Africa and the China, with some regularity, often with considerable severity, and with an impact that is

*Figure 3.3* Variability of precipitation at selected stations in Africa




*Source:* Compiled from data in Landsberg (1986)

felt beyond the areas directly affected. Drought is expected in such areas, but elsewhere it is highly irregular and, as a result, all the more serious. Such was the case in 1976 when the normally humid UK was sufficiently dry that the government felt it necessary to appoint a Minister of Drought.

Drought may also have played a significant role in the historical development of society through its impact on past civilizations. For example, changes in wind circulation and increased aridity in what is now northern Syria from about 2200 BC are thought to have destroyed the agricultural base of the Mesopotamian Subir civilization (Weiss *et al.* 1993), and the decay of the Harrapan civilization in the Indus valley has been linked to the desiccation of that region after 1800 BC (Calder 1974). In Europe, some 3000 years ago, the flourishing Mycenaean civilization of southern Greece went into irreversible decline. The rapidity and extent of the decline was such that it was commonly attributed to the invasion of Mycenae by Greeks from the regions to the north. In 1968, however, Rhys Carpenter reassessed the available evidence, and suggested that no invasion had taken place. Instead, he postulated that drought followed by starvation, social unrest and migration led to the downfall of the Mycenaeans. Climatologists at the University of Wisconsin-Madison developed Carpenter's theory further, and concluded that drought was a major contributory factor in the decay of the civilization (Bryson *et al.* 1974; Bryson and Murray 1977). As in many cases where a climatic explanation is invoked to account for major societal changes in the distant past, the link between the decline of the Mycenaean civilization and drought is not considered convincing by some researchers (see e.g. Parry 1978). The absence of adequate and appropriate data prevents such hypotheses from being developed much beyond the speculative stage.

Modern views of drought vary with time and place and with the nature of the event itself. It may be seen as a technological problem, an economic problem, a political problem, a cultural problem or sometimes a multi-faceted problem involving all of these. Whatever else it may be, however, it is always an environmental problem, and basic to any understanding of the situation is the relationship between society and environment in drought-prone areas.

Over thousands of years, certain plants and animals have adapted to life with limited moisture. Their needs are met, therefore no drought exists. This is the theoretical situation in most arid areas. In reality, it is much more complex, for although the flora and fauna may exist in a state of equilibrium with other elements in the environment, it is a dynamic equilibrium, and the balance can be disturbed. Changes in weather patterns, for example, might further reduce the already limited amount of precipitation available, changing the whole relationship. If the plants and animals can no longer cope with the reduced water supply, they will suffer the effects of drought. Depending upon the extent of the change, plants may die from lack of moisture, they may be forced out of the area as a result of competition with species more suited to the new conditions or they may survive, but at a reduced level of productivity. The situation is more complex for animals, but the response is often easier. In addition to requiring water, they also depend upon the plants for food, and their fate, therefore, will be influenced by that of the plants. They have one major advantage over plants, however. Being capable of movement, they can respond to changing conditions by migrating to areas where their needs can be met. Eventually some degree of balance will again be attained, although certain areas—such as the world's desert margins—can be in a continual state of flux for long periods of time.

The human animal, like other species, is also forced to respond to such changing environmental conditions. In earlier times this often involved migration, which was relatively easy for small primitive communities, living by hunting and gathering, in areas where the overall population was small. As societies changed, however, this response was often no longer possible. In areas of permanent, or even semi-permanent agricultural settlement, with their associated physical and socio-economic structures, migration was certainly not an option—indeed, it was almost a last resort. The establishment of political boundaries, which took no account of environmental patterns, also restricted migration in certain areas. As a result, in those regions susceptible to drought, the tendency, perhaps even the necessity, to challenge the environment grew. If sufficient water was not available from precipitation either it had to be supplied in other ways—by well and aqueduct, for example—or different farming techniques had to be adopted to reduce the moisture need in the first place. The success of these approaches depended very much on such elements as the nature, intensity and duration of the drought, plus a variety of human factors, which included the numbers, stage of cultural development and technological level of the peoples involved.

## Types of drought

C.W.Thornthwaite, the eminent applied climatologist, whose pioneering water balance studies made a major contribution to the understanding of aridity, recognized four types of drought, defined in terms of agricultural requirements (Thornthwaite 1947). These were permanent, seasonal, contingent and invisible drought. Agriculture is not normally possible in areas of permanent drought, since there is insufficient moisture for anything but the xerophytic plants which have adapted to the arid environment. Crops can be produced in such areas, but only at great expense or under exceptional circumstances such as those which apply to the Israeli activities in the Negev Desert, for example (Berkofsky 1986). On the margins of the world's great deserts, there are regions of seasonal drought, where arid conditions prevail for part of the year, but which are balanced by a distinct wet season. Much of India, the Sahel and the southern parts of Africa experience such seasonal drought. Agriculture is carried out, often very successfully, during the wet season, and even during the dry season, if the moisture from the preceding rainy season can be retained. If for some reason the rainy season is curtailed, however, the potential for drought is great, and it is not surprising that areas such as the Sahel and the Indian sub-continent have experienced some of the world's most spectacular and catastrophic droughts. The problem is intensified in drier years by the irregularity with which the rains fall, making planning difficult, if not impossible.

Irregular and variable precipitation is also characteristic of contingent drought. In Thornthwaite's definition, this is experienced in areas which normally have an adequate supply of moisture to meet crop needs. Serious problems arise because the agricultural system is not set up to cope with unpredictable and lengthy periods of inadequate precipitation. The interior plains of North America have suffered from contingent drought for hundreds of years, and the droughts of 1975–76 and 1988–92 in Britain would fit this category also.

The presence of these three types of drought is indicated by physical changes in the soil and vegetation in the areas affected, but there is also a fourth type which is less obvious. This is the so-called invisible drought, which often can be identified only by sophisticated instrumentation and statistical techniques. The crops appear to be growing well, even to the experienced observer, and there is no obvious lack of precipitation. However, moisture requirements are not being met, the crop is not growing at its optimum rate, and the potential yield from the land is reduced.

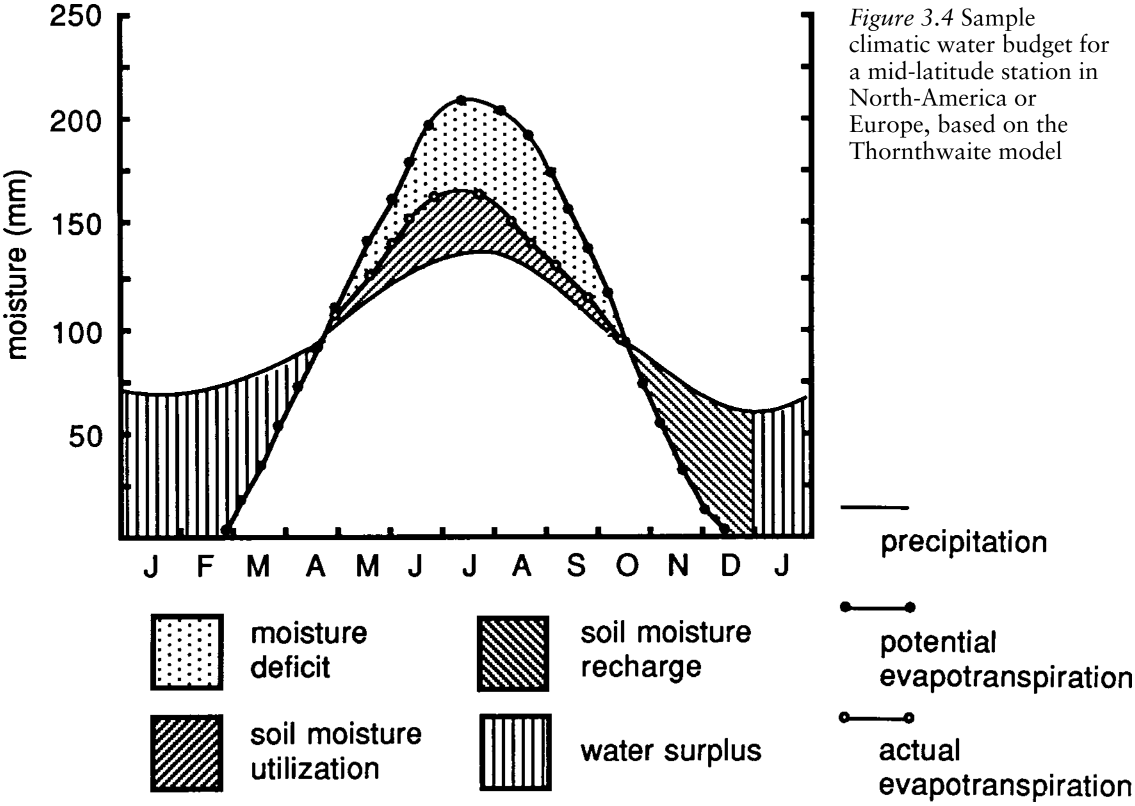



*Figure 3.4* Sample climatic water budget for a mid-latitude station in North-America or Europe, based on the Thornthwaite model

Invisible drought can be dealt with relatively easily by irrigation. In eastern Britain, for example, supplementary moisture has been supplied to sugar beet and potato crops since at least the late 1950s to deal with that problem (Balchin 1964).

## Determination of moisture deficit

To establish the existence of a deficit in an area, it is necessary to compare incoming and outgoing moisture totals. The former is normally represented by precipitation and the latter by evaporation from the earth's surface plus transpiration by plants, commonly combined into one unit referred to as evapotranspiration. In the simplest relationship, if precipitation exceeds evapotranspiration, a water surplus will exist; a water deficit results when the relationship is reversed. Several factors complicate this simple situation. For example, all soils have the ability to store a certain amount of water, and this disturbs the relationship between precipitation and evapotranspiration. If the soil water storage is full, the soil is said to be at field capacity, and any additional precipitation not evaporated is considered as run-off. The presence of soil water will help to offset any water deficit, since, even if the evapotranspiration exceeds precipitation, some or all of the deficit may be made up from the soil moisture storage. This has the effect of delaying the onset of drought until the storage capacity is exhausted, and illustrates one of the dangers of measuring drought by precipitation alone or even by some simple comparison of precipitation and evapotranspiration. Once precipitation is again in excess, the soil water storage must be recharged before a moisture surplus exists.

A second factor complicating the relationship between precipitation and evapotranspiration, and the existence of moisture deficiency, involves the measurement of evapotranspiration. Evapotranspiration will only occur if moisture is available. Thus, if the moisture directly available from precipitation and in storage in the soil is completely exhausted, no evapotranspiration can take place. Yet even when no water is available, the environment may retain the ability to cause evapotranspiration through such elements as temperature, radiation, humidity and air movement. Thornthwaite (1948) developed the concept of potential evapotranspiration to recognize this situation. Potential evapotranspiration may be considered the amount of evaporation and transpiration that would take place if sufficient moisture was available to fill the environment's capacity for evapotranspiration. In this way, the distinction between measurable (actual) and theoretical (potential) amounts of evapotranspiration can be recognized. As long as precipitation exceeds evapotranspiration, the actual and potential values will be the same, but as soon as the situation is reversed the two values begin to deviate at a rate which depends upon the availability of soil moisture. The difference between actual and potential evapotranspiration can be considered as a measure of the water deficit, and agricultural areas experiencing moisture deficiency depend upon this approach to estimate the appropriate amount of moisture required to combat drought or to allow crops to grow at their full potential. The relationships between elements such as precipitation, actual and potential evapotranspiration, water surplus and deficit, as identified by Thornthwaite, are illustrated in Figure 3.4.

Modern methods of drought evaluation tend to focus on the soil moisture deficit (SMD) rather than the basic water deficit represented by the excess of evapotranspiration over precipitation (see e.g. Palutikof 1986). Such factors as the nature and stage of development of the crop, the storage capacity of a specific soil, and the ease with which the crop can extract moisture from the soil are all given greater attention than in Thornthwaite's original approach to the problem. The SMD in a region will not be a specific value, but will vary according to crop and soil conditions. A consistently high SMD over the growing season, however, will ultimately lead to drought unless the situation is recognized and rectified.

Thornthwaite's treatment of the measurement and classification of drought is only one of many. It may not meet all needs, but its broadly climatological approach lends itself to the geographical examination of drought-prone environments. The greatest human impact is felt in those areas which experience seasonal or contingent drought, although the nature of the impact is different in each case. The influence of the other two types of drought is limited. In areas of permanent drought, for example, populations are small, and may exist only under special circumstances, such as those at an oasis, where the effects of the drought are easily countered. Although invisible drought may have important consequences for individuals, it often passes unrecognized. It does not produce the life and death concerns that prevail in areas of seasonal drought, nor does it have the dire economic impacts that may be experienced by the inhabitants of areas of contingent drought.

### Seasonal drought in the sub-tropics

Seasonal drought is most commonly experienced in the sub-tropics. There, the year includes a distinct dry season and a distinct wet season, associated with the north-south movement of the intertropical convergence zone (ITCZ) and its attendant wind and pressure belts (see Figure 2.13).

During the dry season, these areas are dominated by air masses originating in the sub-tropical high pressure systems—which characteristically contain limited moisture, and are dynamically unsuited to produce much precipitation. Anticyclonic subsidence prevents the vertical cloud development necessary to cause rain. In contrast, the rainy season is made possible by the migration of the ITCZ, behind which, the combination of strong convection and air mass convergence promotes the instability and strong vertical growth which leads to heavy rainfall. The passage of the ITCZ—in Africa, India, SE Asia and Australia—allows the incursion of moist, relatively unstable air from the ocean over the land to initiate the wet season. This is the basis of the monsoon circulation in these areas, and it is often the failure of this circulation that sets up the conditions necessary for drought. If, for example, the ITCZ fails to move as far polewards as it normally does, those regions, which depend upon it to provide the bulk of their yearly supply of water, will remain under the influence of the dry air masses, and receive little or no rainfall. Similarly, any increase in the stability of the airflow following the passage of the ITCZ will also cause a reduction in water supply. It is developments such as these that have set the stage for some of the worst droughts ever experienced.

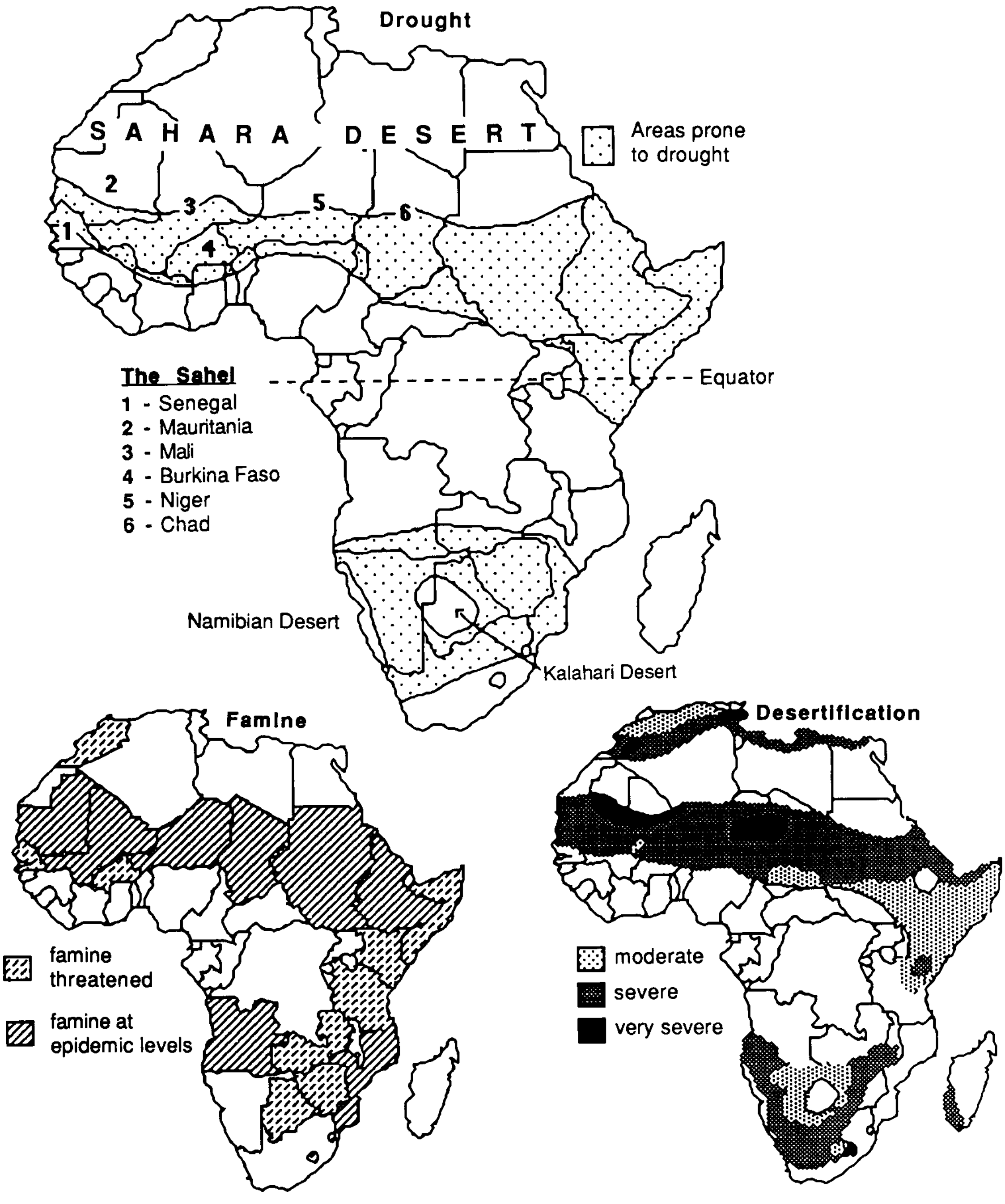
## DROUGHT AND FAMINE IN AFRICA

Although seasonal drought is experienced in all of the world's sub-tropical areas, in recent years the greatest effects have been felt in sub-Saharan Africa, including the region known as the Sahel where drought is much more persistent than elsewhere on the continent (Nicholson 1989). The Sahel proper is that part of western Africa lying to the south of the Sahara Desert and north of the tropical rainforest. It comprises six nations, stretching from Senegal, Mauretania and Mali in the west, through Burkina Faso to Niger and Chad in the east. This region, with its population of 33 million inhabiting slightly more than 5 million sq km of arid or semi-arid land, came to prominence between 1968 and 1973 when it was visited by major drought, starvation and disease. Despite this prominence, it is, in fact, only part of a more extensive belt of drought-prone land in Africa south of the Sahara. Drought pays no heed to political boundaries, reaching as it does to the Sudan, Ethiopia and Somalia in the east and including the northern sections of Ghana, Nigeria, Cameroon, the Central African Republic, Uganda and Kenya. In the 1980s, drought also extended into Mozambique, Zimbabwe and other parts of eastern and southern Africa (see Figure 3.5).

### The atmospheric circulation in sub-Saharan Africa

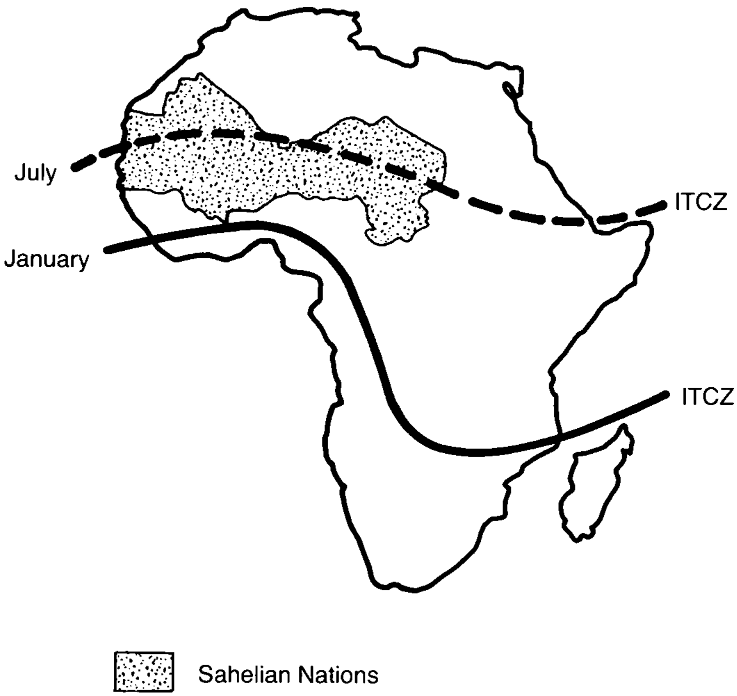
The supply of moisture in all of these areas is

*Figure 3.5* The distribution of drought, famine and desertification in Africa




*Source:* After CIDA (1985)

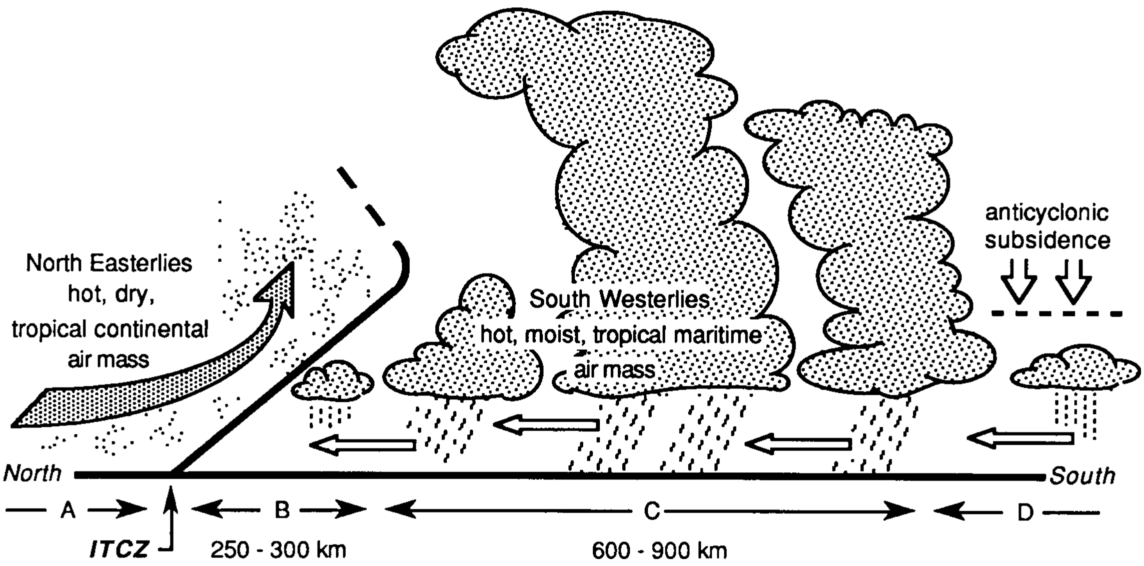
*Figure 3.6* Seasonal changes in the position of the ITCZ in Africa




governed by seasonal fluctuations in the position of the ITCZ. Dry conditions are associated with hot, continental tropical (cT) air, from the Sahara in the west and the Arabian Peninsula in the east, which moves in behind the ITCZ as it migrates southwards during the northern hemisphere's winter. At its most southerly extent, in January or February, the ITCZ remains at about 8 degrees north of the equator in West Africa, but curves sharply southwards across the centre of the continent to reach 15–20°S in East Africa (see Figure 3.6). Apart from East Africa, which receives some precipitation brought in off the Indian Ocean by the north-east trade winds of the winter monsoon, most of the northern part of the continent experiences its dry season at that time. All of West Africa, beyond a narrow strip some 200 km wide along the coast, is under the influence of a north-easterly airflow, from the central Sahara. This is known locally as the Harmattan—a hot, dry wind, which carries with it large volumes of fine dust from the desert. On occasion, the dust is so thick that visibility is reduced to less than 1000 m, and, in combination with the break-up of radio transmissions caused by the high concentration of aerosols, this disrupts local air traffic. The scattering of solar radiation by the Harmattan haze also has broader implications for such activities as agriculture, solar energy engineering and environmental planning (Adetunji *et al.* 1979). At the personal level, the low humidity of the dusty air contributes to discomfort in the form of dry skin, sore throats and cracked lips.

The ITCZ moves north again during the northern summer, and by July and August has reached its most northerly location at about 20°N (see Figure 3.6). Hot, moist, maritime tropical (mT) air flows in behind it, bringing the rainy season. In the east, the moisture is provided by air masses from the Indian Ocean as part of the Asiatic monsoon system, while in the west it arrives in the south westerly flow off the South Atlantic. Although relatively simple to describe

*Figure 3.7* North-South section across West Africa, showing bands of weather associated with the ITCZ



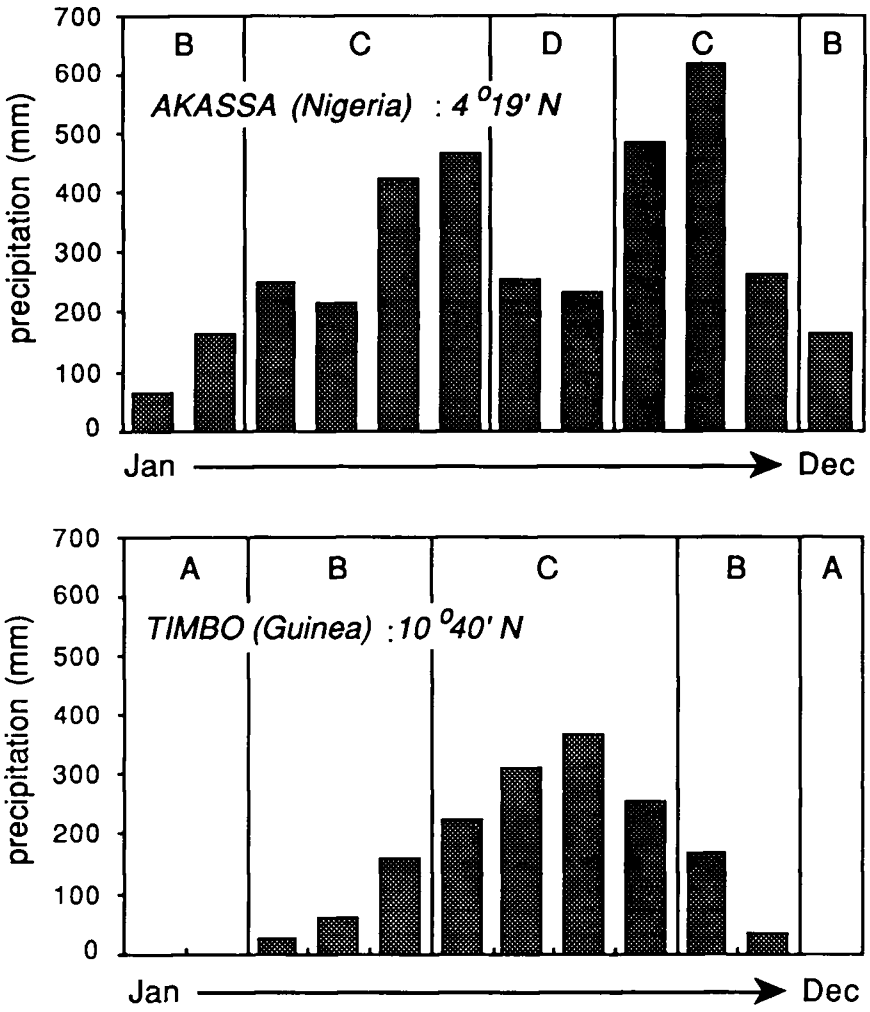

*Source:* After Hamilton and Archbold (1945)

in general terms, in detail the precipitation patterns are quite complex. In West Africa, for example, the existence of four weather zones, aligned east-west in parallel with the ITCZ, was recognized by Hamilton and Archbold in 1945, and these, with some modern modifications (e.g. Musk 1983), provide the standard approach to the regional climatology of the area (see Figure 3.7). Each of the zones is characterized by specific weather conditions, which can be identified in the precipitation regimes of the various stations in the area (see Figure 3.8). The precipitation is caused mainly by convection and convergence, and reaches the ground in a variety of forms, ranging from light, intermittent showers, to the heavy downpours associated with violent thunderstorms or line squalls. The easterly tropical jet is also active in the upper atmosphere at this time, and may well influence the amount, intensity and distribution of precipitation (Kamara 1986).

## Drought and human activity

Throughout the Sahelian region, the peak of the rainy season in July and August is also the time of year when grass and other forage is most widely available for the herds of cattle, camels, goats and sheep belonging to the local agriculturalists. The original herdsmen lived a nomadic existence, following the rains north in the summer and south in the winter, to obtain the food their animals needed. There was sufficient moisture available in the southern areas to allow a more permanent lifestyle, supported by basic arable agriculture, producing sorghum and millet. Drawn south by the rains, the herdsmen eventually encroached upon this farmed land, but instead of the conflict that might have been expected in such a situation, the two societies enjoyed a basic symbiotic relationship. The nomads exchanged meat and milk for grain; the cattle grazed the stubble, and provided fertilizer for the following year's crop.

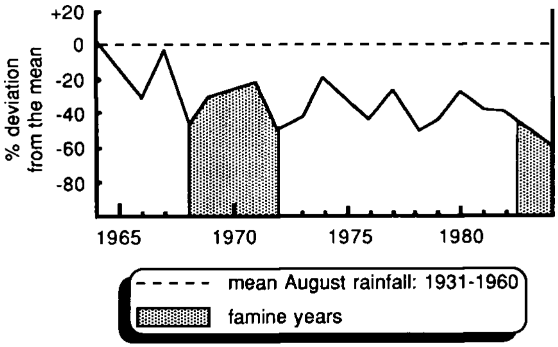
*Figure 3.8* Precipitation regimes in West Africa




Letters A, B, C and D represent the weather zones illustrated in Figure 3.7

Although the movement of the ITCZ is repeated season after season, it shows some irregularity in its timing, and in the latitudinal distance it covers each year. As a result, the rainfall associated with it is never completely reliable, and this is particularly so in those areas close to the poleward limits of its travel (Musk 1983). In West Africa, for example, if the ITCZ fails to reach its normal northern limits at about 20°N, the regions at that latitude will experience drought. The greatest problems arise when such dry years occur in groups. The population might be able to survive one or two years of drought, but a longer series has cumulative effects similar to those in the 1960s and 1970s when consecutive years of drought led to famine, malnutrition,

*Figure 3.9* August rainfall in the Sahel: 1964–84




*Source:* After Cross (1985a)

disease and death. In contrast, good years are those in which the ITCZ, with its accompanying rain, moves farther north than normal, or remains at its poleward limits for a few extra days or even weeks.

In the past, this variability was very much part of the way of life of the drought-prone areas in sub-Saharan Africa. The drought of 1968 to 1973 in the Sahel was the third major dry spell to hit the area this century, and although the years following 1973 were wetter, by 1980 drier conditions had returned (see Figure 3.9). By 1985 parts of the region were again experiencing fully fledged drought (Cross 1985a). A return to average rainfall in 1988 provided some respite, but it was short-lived, and in 1990 conditions again equalled those during the devastating droughts of 1972 and 1973 (Pearce 1991b). Much as the population must have suffered in the past, there was little they could do about it, and few on the outside showed much concern. Like all primitive nomadic populations, the inhabitants of the Sahel increased in good years and decreased in bad, as a result of the checks and balances built into the environment.

That situation has changed somewhat in recent years. The introduction of new scientific medicine, limited though it may have been by Western standards, brought with it previously unknown medical services—such as vaccination programmes—and led to improvements in child nutrition and sanitation. Together these helped to lower the death rate, and, with the birth rate remaining high, populations grew rapidly, doubling between 1950 and 1980 (Crawford 1985). The population of the Sahel grew at a rate of 1 per cent per annum during the 1920s, but by the time of the drought in the late 1960s the rate was as high as 3 per cent (Ware 1977). Similar values have been calculated for the eastern part of the dry belt in Somalia (Swift 1977) and Ethiopia (Mackenzie 1987b). Initially, even such a high rate of growth produced no serious problems, since in the late 1950s and early 1960s a period of heavier more reliable rainfall produced more fodder, and allowed more animals to be kept. Crop yields increased also in the arable areas. Other changes, with potentially serious consequences, were taking place at the same time, however. In the southern areas of the Sahel, basic subsistence farming was increasingly replaced by the cash-cropping of such commodities as peanuts and cotton. The way of life of the nomads had already been changed by the establishment of political boundaries in the nineteenth century, and the introduction of cash-cropping further restricted their ability to move as the seasons dictated. Commercialization had been introduced into the nomadic community also, and in some areas market influences encouraged the maintenance of herds larger than the carrying capacity of the land. This was made possible, to some extent by the drilling or digging of new wells, but as Ware (1977) has pointed out, the provision of additional water without a parallel provision of additional pasture only served to aggravate ecological problems. All of these changes were seen as improvements when they were introduced, and from a socio-economic point of view they undoubtedly were. Ecologically, however, they were suspect, and, in combination with the dry years of the 1960s, 1970s and 1980s, they contributed to disaster.

The grass and other forage dried out during the drought, reducing the fodder available for the animals. The larger herds—which had grown up during the years of plenty—quickly stripped the available vegetation, and exposed the land to soil erosion. The water holes, and eventually even the rivers, dried up, and those animals that had not died of starvation died of thirst. When the nomads tried to move they found that it was no longer as easy as it had once been. The farmers who had formerly welcomed the pastoralists for the meat and milk they supplied and for the natural fertilizer from their animals, no longer wanted herds trampling fields which, with the aid of irrigation, were being cropped all year round. Furthermore, growing peanuts and cotton, and only a little food for their own use, they had no excess left for the starving nomads. Eventually, as the drought continued, the farmers suffered also. There was insufficient water for the irrigation systems, the artificial fertilizers that had replaced the animal product was less effective at low moisture levels, and yields were reduced dramatically. In a desperate attempt to maintain their livelihood, they seeded poorer land, which was soon destroyed by soil erosion in much the same way as the overgrazed soil of the north had been.

The net result of such developments was the death of millions of animals—probably 5 million cattle alone—and several hundred thousand people. The latter numbers would have been higher, but for the outside aid which provided for 7 million people at the peak of the drought in the Sahel between 1968 and 1973 (Glantz 1977). Similar numbers were involved in Ethiopia between 1983 and 1985, although accurate figures are difficult to obtain because of civil war in the area (Cross 1985b). Drought and locusts destroyed crops in the northern Ethiopian provinces of Tigray and Eritrea again in 1987, and the UN World Food Program estimated that as many as 3 million inhabitants were put at risk of starvation and death (Mackenzie 1987a). Elsewhere—in Kenya, Uganda, Sudan, Zimbabwe and Mozambique—severe drought continued into the 1990s. Even in the Sahel, which had experienced some improvement in the late 1970s, increasing aridity after 1980 was the precursor of the more intense drought affecting the area once again. The death of the animals, the destruction of the soil and indeed the destruction of society has meant that all of sub-Saharan Africa—from Senegal to Somalia—remains an impoverished region, dependent upon outside aid and overshadowed by the ever present potential for disaster the next time the rains fail, as fail they will.

## DROUGHT ON THE GREAT PLAINS

Since all of the nations stricken by drought in sub-Saharan Africa are under-developed, it might be considered that lack of economic and technological development contributed to the problem. To some extent it did, but it is also quite clear that economic and technological advancement is no guarantee against drought. The net effects may be lessened, but the environmental processes act in essentially the same way, whatever the stage of development.

This is well illustrated in the problems faced by farmers on the Great Plains that make up the interior of North America (see Figure 3.10). Stretching from western Texas in the south, along the flanks of the Rocky Mountains to the Canadian prairie provinces in the north, they form an extensive area of temperate grassland with a semi-arid climate. They owe their aridity in part to low rainfall, but the situation is aggravated by the timing of the precipitation, which falls mainly in the summer months, when high temperatures cause it to be rapidly evaporated (see Figure 3.11). Contingent drought, brought about by the variable and unpredictable nature of the rainfall, is characteristic of the area—consecutive years may have precipitation 50 per cent above normal or 50 per cent below normal—and this has had a major effect on the settlement of the plains. Averages have little real meaning under such conditions, and agricultural planning is next to impossible. The tendency for wet or dry years to run in series introduces further complexity. Strings of dry years during the exploration of the western plains in the

*Figure 3.10* The Great Plains of North America

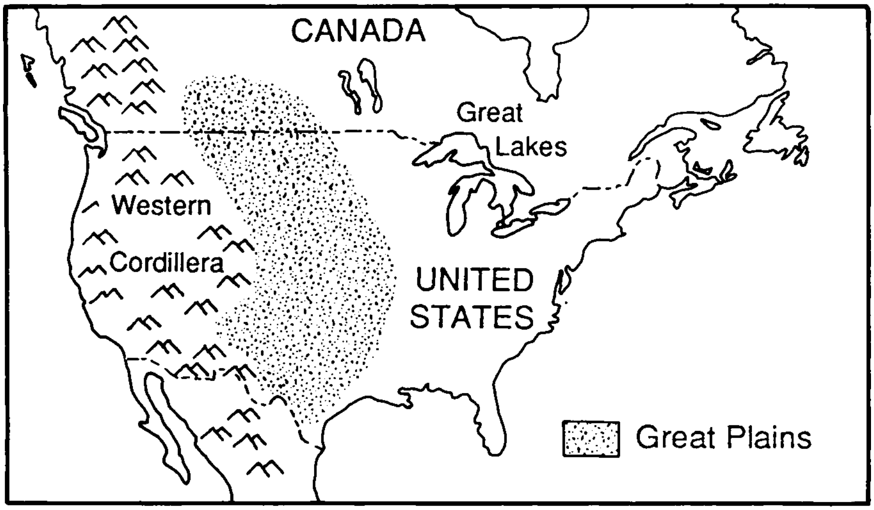
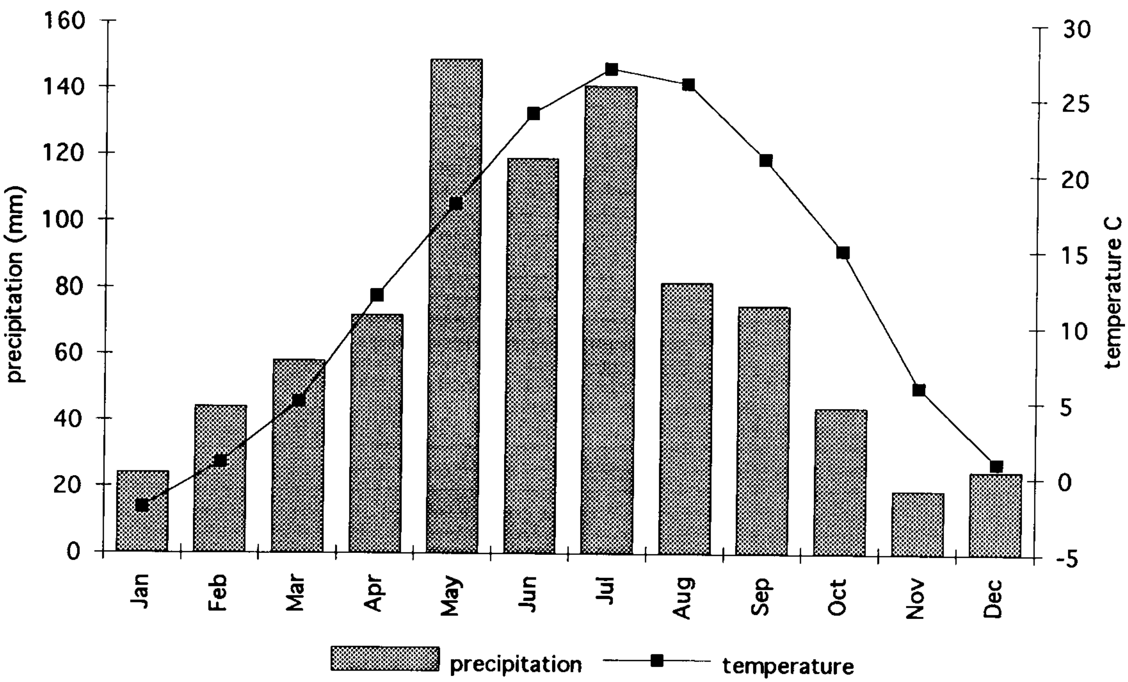



*Figure 3.11* Graph of temperature and precipitation for Topeka, Kansas



nineteenth century, for example, gave rise to the concept of the Great American Desert. Although the concept has been criticized for being as much myth as reality, it is now evident that several expeditions to the western United States in the early part of the century (Lawson and Stockton 1981), and some decades later to western Canada (Spry 1963), encountered drought conditions which are now known to be quite typical of the area, and which have been repeated again and again since that time.

### Historical drought

Local drought is not uncommon on the plains. Almost every year in the Canadian west there are areas which experience the limited precipitation and high temperatures necessary for increased aridity (McKay *et al.* 1967), and archaeological evidence suggests that from the earliest human habitation of the plains it has been so (Van Royen 1937). The original inhabitants, who were nomadic hunters, probably responded in much the same way as the people of the Sahel, when drought threatened. They migrated, following the animals to moister areas. At times, even migration was not enough. For example, during the particularly intense Pueblo drought of the thirteenth century, the population was much reduced by famine (Fritts 1965). Major drought episodes, extensive in both time and place, are also a recurring feature of the historical climatology of the Great Plains (Bark 1978; Kemp 1982), with the groups of years centred on 1756, 1820 and 1862 being particularly noteworthy (Meko 1992).

The weather was wetter than normal when the first European agricultural settlers moved into the west in the late 1860s following the Civil War. The image of the Great American Desert had paled, and the settlers farmed just as they had done east of the Mississippi or in the mid-west, ploughing up the prairie to plant wheat or corn. By the 1880s and 1890s, the moist spell had come to an end, and drought once more ravaged the land (Smith 1920), ruining many settlers and forcing them to abandon their farms. Ludlum (1971) has estimated that fully half the settlers in Nebraska and Kansas left the area at that time, like the earlier inhabitants, seeking relief in migration, in this case back to the more humid east. Some of those who stayed experimented with dry-farming, but even that requires a modicum of moisture if it is to be successful. Others allowed the land to revert to its natural state, and used it as grazing for cattle, a use for which it was much more suited in the first place. The lessons of the drought had not been learned well, however. Later, in the 1920s, the rains seemed to have returned to stay and a new generation of arable farmers moved in. Lured by high wheat prices, they turned most of the plains over to the plough, seemingly unconcerned about the previous drought (Watson 1963). Crops were good, as long as precipitation remained above normal. By 1931, however, the good years were all but over, and the drought of the 1930s, in combination with the Depression, created such disruption of the agricultural and social fabric of the region that the effects have reverberated down through the decades. Even today, every dry spell is compared to the benchmark of the Dustbowl. The only possible response for many of the drought victims of the 1930s was migration, as it had been in the past. The Okies of *The Grapes of Wrath,* leaving behind their parched farms, had much in common with the Indians who had experienced the Pueblo drought six centuries before. The societies were quite different, but they felt the same pressures, and responded in much the same way. By migrating, both were making the ultimate adjustment to a hostile environment.

If the drought of the 1930s brought with it hardship and misery, it also produced, finally, the realization that drought on the plains is an integral part of the climate of the area. Intense dry spells have recurred since then—particularly in the mid 1970s and early 1980s (Phillips 1982) and again in 1987 and 1988—causing significant disruption at the individual farm and local level. Because of the general acceptance of the limitations imposed by aridity, however, the overall impact was less than it would have been half a century earlier. New agricultural techniques—involving dry farming as well as irrigation—coupled with a more appropriate use of the land, help to offset the worst effects of the arid environment, but some problems will always remain.

### Dry farming and irrigation

Dry farming is based on the preservation of several years of precipitation to be used for the production of one crop. The land is deep ploughed and allowed to lie fallow for several years. Deep ploughing provides a reservoir for the rain that falls, and various techniques are used to reduce losses by evapotranspiration. Perhaps only a quarter of the total precipitation is made available to the plants in this way, but in Kansas and Nebraska grain yields may double after a three- to four-year fallow (More 1969). Obviously, this is only possible if rain falls in the first place. It might be necessary to counter the lack of precipitation by introducing water from elsewhere in the hydrologic cycle, and making it available through direct irrigation. Most of the major rivers on the plains have been dammed and the underlying aquifers tapped to provide the moisture required. Grandiose schemes, such as the North American Water and Power Alliance (NAWAPA), which would bring water to the plains from the Hudson Bay and Arctic watersheds in northern Canada, have also been suggested (Schindler and Bayley 1990). While this may be ideal for agriculture, it is not without its environmental problems. The larger projects have been roundly criticized for their ability to cause continental scale environmental disruption, but even local or regional schemes can be harmful. The rivers downstream from dams experience reduced flow, which produces physical changes in the stream channel and disrupts the balance in the aquatic environment. Return flow from irrigated fields contains fertilizer and pesticide residues, which alter the chemical composition of the water. The classic example of such changes is the Colorado River, which at its mouth is a mere trickle of highly salinated water, flowing in a channel much larger than the present volume requires (Turk 1980).

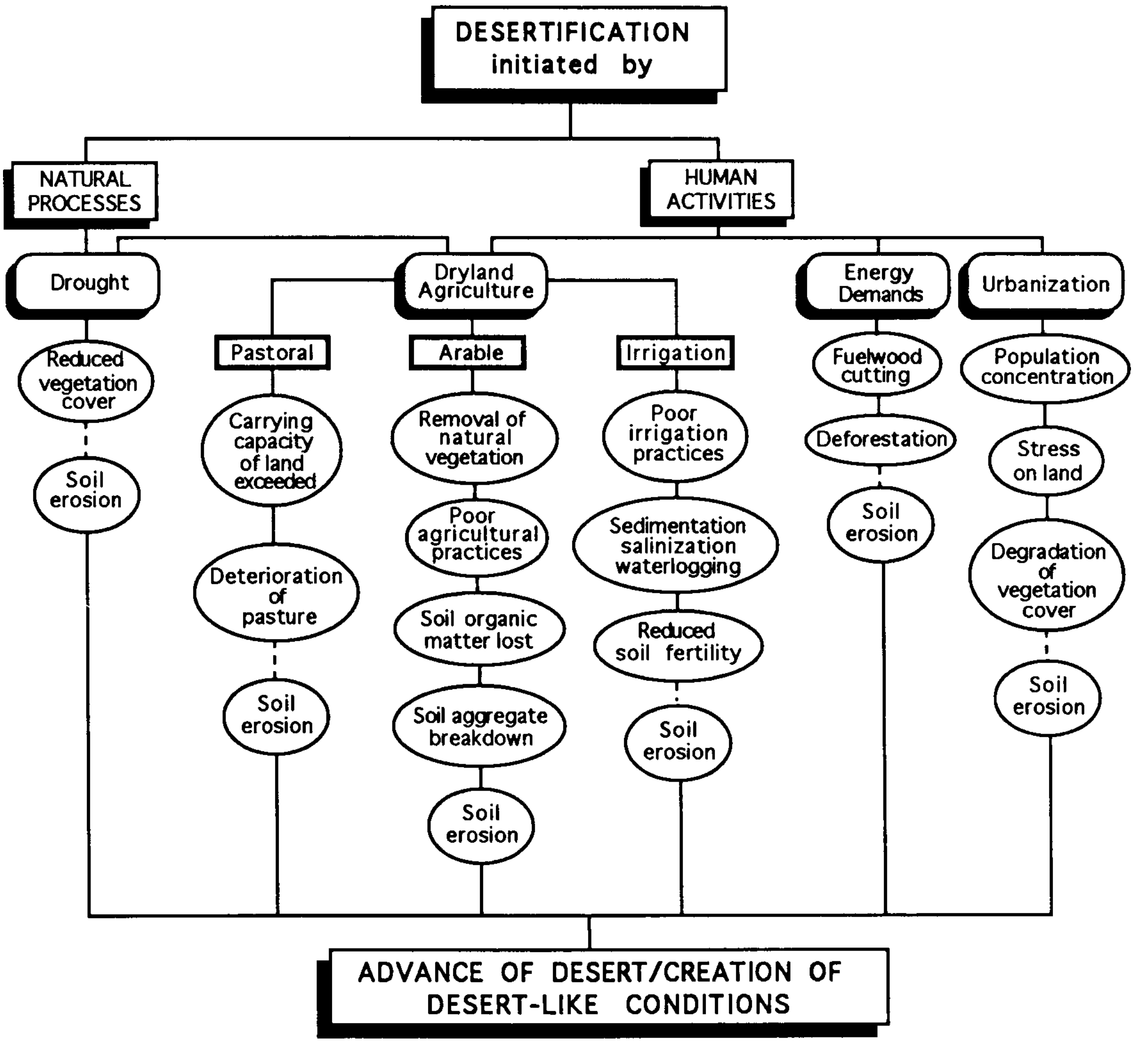
Agriculture has resorted to the use of groundwater in those areas with no fluvial water supply available. Groundwater has several advantages over surface water, such as reliability of supply and uniform quality, but many of the aquifers beneath the plains have been so extensively used that the recharge rate has fallen far behind demand, and they are becoming depleted. This, in turn, leads to the need for deeper wells, and increased pumping time, with a consequent rise in costs.

Whatever the source of the additional moisture, irrigation has one major problem associated with it worldwide, that is the growth of salinization or the build up of salts in the upper layers of the soil. It is a problem as old as irrigation itself (see e.g. Jacobsen and Adams 1971). In areas of high temperature, evaporation rates are generally high, and this causes the salinity of surface water in these areas to be high. Groundwater also tends to have a high salt level, particularly if it has been in the system for a long time. When the water is applied to the crops, the evaporation loss is high, and the salts remain behind in the soil after the water has evaporated. The salt build-up may be so great over time that it interferes with the growth processes in the plants, and they die or provide only much reduced yields. In some cases, the salt may be flushed out of the soil, but the process is costly, and not always completely successful. As a result, land which has been affected by salinization may have to be abandoned.

There are also economic factors which must receive consideration along with these physical problems. Although modern irrigation techniques are remarkably successful, they are also costly; a modern central pivot system, for example, will require an investment well in excess of $1000 per hectare. The capital costs of providing equipment to combat drought, in areas of contingent drought, such as the Great Plains, where major drought may occur perhaps only every 15 to 20 years, have to be weighed against the losses that would occur if no action is taken.

Losses of as much as $16 billion have been reported for the 1980 drought in the US Great Plains (Karl and Quayle 1981), and a figure of $2.5 billion has been estimated for the 1984 drought on the Canadian prairies (Sweeney 1985). Amounts such as these would seem to support investment in irrigation equipment, but such direct economic considerations may not always satisfy environmental concerns. If the investment is made, there may be a tendency to introduce irrigation into areas not particularly suited to arable agriculture, rather than have equipment lying idle. This may create no problems in the short term, but, during the longer periods of drought common on the plains, these areas would be the first to suffer. If no investment is made, in times of drought there may be an attempt to offset the lower yields by bringing more land under cultivation. Whatever the decision, the net result is that additional land

*Figure 3.12* The causes and development of desertification



becomes susceptible to environmental degradation.

## DESERTIFICATION

Although often severe, the problems which arise in most areas experiencing seasonal or contingent drought are seen as transitory, disappearing when the rains return. If the rains do not return, the land becomes progressively more arid until, eventually, desert conditions prevail. This is the process of desertification in its simplest form. When considered in this way, desertification is a natural process which has existed for thousands of years, is reversible, and has caused the world's deserts to expand and contract in the past. This is, however, only one approach to desertification—one which sees the process as the natural expansion of desert or desert-like conditions into an area where they had not previously existed. This process, occurring along the tropical desert margins, was referred to originally as 'desertization' (Le Houerou 1977), but the more common term now is 'desertification', and the concept has been expanded to include a human element.

There is no widely accepted definition of desertification. Most modern approaches, however, recognize the combined impact of adverse climatic conditions and the stress created by human activity (Verstraete 1986). Both have been accepted by the United Nations as the elements that must be considered in any working definition of the process (Glantz 1977). The United Nations Environment Program (UNEP) has tended to emphasize the importance of the human impact over drought, but the relative importance of each of these elements remains very controversial. Some see drought as the primary element, with human intervention aggravating the situation to such an extent that the overall expansion of the desert is increased, and any recovery—following a change in climatic conditions, for example—is lengthier than normal. Others see direct human activities as instigating the process. In reality, there must be many causes (see Figure 3.12) which together bring desert-like conditions to perhaps as much as 60,000 sq km of the earth's surface every year and threaten up to 30 million sq km more. The areas directly threatened are those adjacent to the deserts on all continents. Africa is currently receiving much of the attention, but large sections of the Middle East, the central Asian republics of the former Soviet Union, China adjacent to the Gobi Desert, northwest India and Pakistan, along with parts of Australia, South America and the United States are also susceptible to desertification. Even areas not normally considered as threatened, such as southern Europe from Spain to Greece, are not immune (see Figure 3.2b). At least 50 million people are directly at risk of losing life or livelihood, in these regions. In a more graphic illustration of desertification, the United States Agency for International Development (USAID), at the height of the Sahelian drought in 1972, claimed that the Sahara was advancing southwards at a rate of as much as 30 miles (48 km) (Pearce 1992f). Although these specific numbers are not universally accepted—Nelson (1990), for example, has suggested that all such data be treated with a healthy scepticism—they do give an indication of the magnitude of the problem, and the reason that there has been increasing cause for concern in recent years (van Ypersele and Verstraete 1986).

### Desertification initiated by drought

Human nature being what it is, attitudes to drought include a strong element of denial, and when drought strikes there is a natural tendency to hope that it will be short and of limited intensity. According to Heathcote (1987), for example, the traditional Australian approach to drought has been to denigrate it as a hazard and to react to its onset with surprise. The inhabitants of drought-prone areas, therefore, may not react immediately to the increased aridity, particularly if they have progressed beyond the hunting/gathering socio-economic level. They may continue to cultivate the same crops, perhaps even increasing the area under cultivation to compensate for reduced yields, or they may try to retain flocks and herds which have expanded during the times of plenty. If the drought is prolonged in the arable areas, the crops die and the bare earth is exposed to the ravages of soil erosion. The Dustbowl in the Great Plains developed in this way. Once the available moisture had been evaporated, and the plants had died, the wind removed the topsoil—the most fertile part of the soil profile—leaving a barren landscape, which even the most drought-resistant desert plants found difficult to colonize (Borchert 1950). In the absence of topsoil there was nothing to retain the rain which did fall. It rapidly ran off the surface, causing further erosion, or percolated into the ground-water system where it was beyond the reach of most plants.

Prolonged drought in pastoral areas is equally damaging. It reduces the forage supply, and, if no attempt is made to reduce the animal population, the land may fall victim to overgrazing. The retention of larger herds during the early years of the Sahelian drought, for example, allowed the vegetation to be overgrazed to such an extent that even the plant roots died. In their desperation for food, the animals also grazed on shrubs and even trees, and effectively removed vegetation which had helped to protect the land. The flocks and herds had been depleted by starvation and death by the time this stage was reached, but the damage had been done. The wind, its speed unhampered by shrubs and trees, lifted the exposed, loose soil particles and carried them away, taking with them the ability of the land to support plant and animal life. In combination these human and physical activities seemed to be pushing the boundaries of the Sahara Desert inexorably southwards, to lay claim to territory which only recently supported a population living as comfortably as it could within the constraints of the environment. Out of this grew the image of the 'shifting sands', which came to represent desertification in the popular imagination. As an image, it was evocative, but the reality of such a representation has been increasingly questioned in the 1990s (Nelson 1990; Pearce 1992f).

### Desertification caused by human activity

Climatic variability clearly made a major contribution to desertification, in both the Sahel and the Great Plains—perhaps even initiating the process—and in concert with human activities created serious environmental problems. An alternative view sees human activity in itself capable of initiating desertification in the absence of increased aridity (Verstraete 1986). For example, human interference, in areas where the environmental balance is a delicate one, might be sufficient to set in motion a train of events leading eventually to desertification. The introduction of arable agriculture into areas more suited to grazing, or the removal of forest cover, to open up agricultural land or to provide fuelwood, may disturb the ecological balance to such an extent that the quality of the environment begins to decline. The soil takes a physical beating during cultivation: its crumb structure is broken down and its individual constituents are separated from each other. In addition, cultivation destroys the natural humus in the soil and the growing crops remove the nutrients, both of which normally help to bind the soil particles together into aggregates. If nothing is done to replace the organic material or the nutrients, the soil then becomes highly susceptible to erosion. Modern agricultural techniques, which allow the soil to lie exposed and unprotected by vegetation, for a large part of the growing season, also contribute to the problem. When wind and water erode the topsoil it becomes impossible to cultivate the land, and even natural vegetation has difficulty re-establishing itself in the shifting mineral soil that remains.

The removal of trees and shrubs to be used as fuel has had similar effects in many Third World nations, where the main source of energy is wood. In Sudan, for example, the growing demand for fuelwood was a major factor in the reduction of the total wood resource by 3.6 per cent annually in the 1970s and early 1980s (Callaghan *et al.* 1985). Le Houerou (1977) has estimated that, in the areas along the desert margins in Africa and the Middle East, a family of five will consume, every year, all of the fuel available on one hectare of woody steppe. With a population close to 100 million dependent upon this form of fuel in the area concerned, as much as 20 million hectares per year are being destroyed, and all of that area is potentially open to desertification.

No change in the land-use is required to initiate such a progression, in some regions. The introduction of too many animals into an area may lead to overgrazing and cause such environmental deterioration that after only a few years the land may no longer be able to support the new activity. Forage species are gradually replaced by weeds of little use to the animals, and the soil becomes barren and unable to recover even when grazing ceases. In all of these cases, the land has been laid waste with little active contribution from climate. Human activities have disturbed the environmental balance to such an extent that they have effectively created a desert.

Although human activities have been widely accepted as causing desertification, and the processes involved have been observed, there is increasing concern that the human contribution has been overestimated. Current academic and popular attitudes to desertification owe a lot to the findings of a United Nations Conference on Desertification (UNCOD) held in Nairobi, Kenya in 1977. At that conference, the role of human activities in land degradation was considered to be firmly established, and the contribution of drought was seen as secondary at best. Since human action had caused the problem, it seemed to follow that human action could solve it. In keeping with this philosophy, UNEP was given the responsibility for taking global initiatives to introduce preventive measures which would alleviate the problem of desertification (Grove 1986). Fifteen years and $6 billion later, few effective counter measures have been taken, and the plan of action is widely seen as a failure (Pearce 1992a).

The data upon which the UNEP responses were based are now considered by many researchers to be unrepresentative of the real situation. Nelson (1990), for example, has suggested that the extent of irreversible desertification has been over-estimated, although he does not deny that it remains a serious concern in many parts of the world. The main problems with the data arose from the timing and method of collection, and were aggravated by the UNEP premise that human activity was the main cause of the land degradation that produced desertification. The basic data, apparently indicating the rapid creation of desert-like conditions, were collected in the early 1970s at a time of severe drought in sub-Saharan Africa. They therefore failed to give sufficient weight to the marked rainfall variability characteristic of the area, and in consequence over-represented the effects of the drought. A great deal of the information was obtained using remote sensing. The changing location of vegetation boundaries were identified from satellite photography, for example. This seemed to confirm the steady encroachment of the desert in areas such as the Sudan, and the results were incorporated in the UNCOD report of 1977. Since then, however, they have been widely disputed, and subsequent studies have found no evidence that the large scale desertification described in the 1970s continued into the 1980s. (For summaries of current thinking on desertification see Nelson (1990), Pearce (1992f) and Hulme and Kelly (1993).)

Failure to appreciate the the extent of annual fluctuations in vegetation boundaries—differences of as much as 200 km were reported on the Sudan/Chad border between 1984 and 1985—combined with inadequate ground control may have contributed to the problem (Nelson 1990). A general consensus seems to be forming among those investigating the issue that the approach to defining desertification in terms of vegetation needs to be re-examined. In parts of East Africa, for example, drought and possibly overgrazing have combined to allow the normal grass cover to be replaced by thorn scrub. On satellite photography this appears as an improvement in vegetative cover, yet from a human and ecological viewpoint it is a retrograde step (Warren and Agnew 1988). A more accurate approach to land degradation might be to study the soil. Vegetation responds rapidly to short-term changes in moisture, but damage to soil takes much longer to reverse. Thus, the measurement of soil conditions—nutrient levels, for example—might give a more accurate indication of the extent of land degradation (Pearce 1992f).

UNEP's insistence on explaining most desertification as the result of human activities may also have contributed to the misrepresentation of the extent of the problem. Natural causes such as short-term drought and longer-term climatic change were ignored or given less attention than they deserved, yet both can produce desert-like conditions without input from society. With short-term drought, the vegetation recovers once the drought is over; with changes induced by lengthier fluctuations, little improvement is likely even if the human use of the land is altered. The inclusion of areas suffering from short-term drought may well have inflated the final results in the UNEP accounting of land degradation. Failure to appreciate the various potential causes of desertification would also limit the response to the problem. Different causes would normally elicit different responses, and UNEP's application of the societal response to all areas, without distinguishing the cause, may in part explain the lack of success in dealing with the problem (Pearce 1992f).

*Table 3.3* Action required for the prevention and reversal of desertification

**1 Prevention**

- a Good land-use planning and management
  - e.g. cultivation only where and when precipitation is adequate
  - animal population based on carrying capacity of land in driest years
  - maintenance of woodland where possible
- b Irrigation appropriately managed to minimize sedimentation, salinization and waterlogging
- c Plant breeding for increased drought resistance
- d Improved long-range drought forecasting
- e Weather modification
  - e.g. rainmaking
  - snowpack augmentation
- f Social, cultural and economic controls
  - e.g. population planning
  - planned regional economic development
  - education

**2 Reversal**

- a Prevention of further soil erosion
  - e.g. by contour ploughing
  - by gully infilling
  - by planting or constructing windbreaks
- b Reforestation
- c Improved water use
  - e.g. storage of run-off
  - well-managed irrigation
- d Stabilization of moving sand
  - e.g. using matting
  - by re-establishment of plant cover
  - using oil waste mulches and polymer coating
- e Social, cultural and economic controls
  - e.g. reduction of grazing animal herd size
  - population resettlement

## The prevention and reversal of desertification

The debunking of some of the myths associated with desertification, and the realization that even after more than 15 years of study its nature and extent are inadequately understood, does not mean that desertification should be ignored. There are undoubtedly major problems of land degradation in many of the earth's arid lands. Perhaps sensing an increased vulnerability as a result of the current controversy, and certainly fearful of being left behind in the rush to deal with the problems of the developed world, the nations occupying the land affected appeared at the Rio Earth Summit in 1992, and proposed a Desertification Convention to address their problems. Despite its lack of success following UNDOC, the provisions of the Convention are likely to be managed by UNEP, which has proposed a budget of $450 billion over 20 years (Pearce 1992f).

Although obscured by the current controversy and lost in the complexity of the attempts to define the issue of desertification more accurately, two questions remain of supreme importance to the areas suffering land degradation. Can desertification be prevented? Can the desertification which has already happened be reversed? In the past, the answer to both has always been a qualified yes (see Table 3.3) and seems likely to remain so, although some researchers take a more pessimistic view (e.g. Nelson 1990). In theory, society could work with the environment by developing a good understanding of environmental relationships in the threatened areas or by assessing the capability of the land to support certain activities, and by working within the constraints that these would provide. In practice, non-environmental elements—such as politics and economics—may prevent the most ecologically appropriate use of the land. A typical response to the variable precipitation, in areas prone to desertification, is to consider the good years as normal and to extend production into marginal areas at that time (Riefler 1978). The stage is then set for progressive desertification when the bad years return. Experience in the United States has shown that this can be prevented by good land-use planning, which includes not only consideration of the best use of the land, but also the carrying capacity of that land under a particular use (Sanders 1986). To be effective in an area such as Africa, this would involve restrictions on grazing and cultivation in many regions, but not only that. Estimates of the carrying capacity of the land would have to be based on conditions in the worst years rather than in the good or even normal years (Kellogg and Schneider 1977; Mackenzie 1987b). Such actions would undoubtedly bring some improvement to the situation, but the transition between the old and new systems might well be highly traumatic for the inhabitants of the area. Stewart and Tiessen (1990), for example, point out that in the Sahel cattle are a form of crop insurance. When the crops fail, farmers plan to survive by selling some of their cattle. Any attempt to limit herds, and prevent overgrazing, must therefore be accompanied by a suitable replacement for this traditional safety net. Without it the pastoralists would lose the advantages of larger flocks and herds in the good years. Some of the cultivators might have to allow arable land to revert to pasture—or reduce cash-cropping and return to subsistence agriculture—and members of both groups might have to give up their rural life-style and become urbanized.

As with the other elements associated with land degradation, the widely accepted relationship that linked growing numbers of livestock to overgrazing and the eventual onset of desertification, has been questioned (Nelson 1990). This in turn has led to a reassessment of the methods by which desertification in pastoral areas can be prevented. Traditional herding techniques involving nomadism and the acceptance of fluctuating herd sizes seem particularly suited to the unpredictable environment of an area such as the Sahel. The nomadic herdsmen of that region may in fact be better managers of the land than the farmers in the wetter areas to the south (Warren and Agnew 1988; Pearce 1992f). They may also know more about dealing with pastoral land-use problems than they are given credit for by scientists from the developed nations. Pearce (1992f) has concluded that there is no evidence that nomadic herdsmen in places like the Sahel actually destroy their pastures. They represent the best way to use land in an area where there is no natural ecological equilibrium, only constant flux. That situation may apply only as long as the flux remains within certain established limits. Too much change in one direction, as occurs during major drought episodes, without concomitant change in herding methods could still encourage desertification. Although the links between herd size, overgrazing and land degradation are considered less firm than was once thought, they have not yet been disproved, and it does not follow that they are entirely absent. In attempts to deal with desertification in pastoral areas, such links cannot be ignored. They clearly need additional investigation.

The problem of the destruction of woodland will also have to be addressed if desertification is to be prevented. Trees and shrubs protect the land against erosion, yet they are being cleared at an alarming rate. One hundred years ago in Ethiopia, 40 per cent of the land could be classified as wooded; today only 3 per cent can be designated in that way (Mackenzie 1987b). Good land-use planning would recognize that certain areas are best left as woodland, and would prevent the clearing of that land for the expansion of cultivation or the provision of fuel wood. The latter problem is particularly serious in most of sub-Saharan Africa where wood is the only source of energy for most of the inhabitants. It also has ramifications which reach beyond fuel supply. Experience has shown that where wood is not available animal dung is burned as a fuel, and although that may supply the energy required, it also represents a loss of nutrients which would normally have been returned to the soil. Any planning involving the conservation of fuelwood must consider these factors, and make provision for an alternative supply of energy or another source of fertilizer.

Many of the techniques which could be employed to prevent desertification are also considered capable of reversing the process. Certainly there are areas where the destruction of the land is probably irreversible, but there have also been some successes. In parts of North America, land apparently destroyed in the 1930s has been successfully rehabilitated through land-use planning and direct soil conservation techniques such as contour ploughing, strip cropping and the provision of windbreaks. Irrigation has also become common, and methods of weather modification, mainly rain making, have been attempted, although with inconclusive results (Rosenberg 1978). Many of these methods could be applied with little modification in areas, such as Africa, where desertification is rampant. Dry-farming techniques have been introduced into the Sudan (CIDA 1985); in Ethiopia, new forms of cultivation similar to contour ploughing have been developed to conserve water and prevent erosion (Cross 1985b); in Mali and other parts of West Africa, reforestation is being attempted to try to stem the southward creep of the desert (CIDA 1985). Most observers consider the success rate of such ventures to be limited (Pearce 1992f). Problems arise from the introduction of inappropriate technology, from the unwillingness of farmers or pastoralists to adopt the new methods and from a variety of economic factors, including, for example, fertilizer costs and the availability of labour (Nelson 1990). There is clearly no universal panacea for desertification. Solutions will have to continue to be specific to the issue and the location, but even then there can be no guarantee that solutions which appear ideal in the short-term will not ultimately exacerbate the problem. The lack of moisture has been tackled directly in many areas, for example, by the drilling of boreholes to provide access to groundwater. Logical as this may seem, without strict control, it may not be the best approach. Extra water encourages larger flocks and herds which overgraze the area around the borehole. Le Houerou (1977) has pointed out that around some of the boreholes drilled at the time of the Sahelian drought, the pasture was completely destroyed within a radius of 15–30 km around the bore. Subsequent investigation, however, has suggested that this was primarily a local problem at only a few wells, and its impact was therefore much less than originally estimated (Pearce 1992f).

All of these developments deal directly with the physical symptoms of desertification, but it has been argued that many studies have overlooked economic and social constraints (Hekstra and Liveman 1986). Ware (1977) has suggested, for example, that insufficient development of markets, transportation and welfare systems made a major contribution to the problems in the Sahel, and future planning must give these factors due consideration. The profit motive is also an important factor in some areas. In Kenya, experience in agroforestry schemes indicates that the best results are achieved when the farmers can see clear and immediate rewards in addition to the less obvious longer-term environmental benefits (Pégorié 1990). On the human side, population growth rates and densities must be examined with a view to assessing human pressure on the land. Over-population has traditionally been regarded as an integral part of the drought/famine/ desertification relationship, but that too has been re-examined. Mortimore (1989), for example, has suggested that high population densities may not be out of place in areas where proposed soil and water conservation schemes are labour intensive. Ironically, some areas suffer from rural depopulation. In the early 1980s, urban populations across Africa increased at about 6 per cent per year, due in large part to the exodus from rural areas (Grove 1986). Where relief from population pressure is needed, it may come in the form of family planning or through relocation. Despite potentially serious social and political concerns, these may be the only ways to tackle the population problem (Mackenzie 1987b).

The fight against desertification has been marked by a distinct lack of success. Recent reassessments of the problem, beginning in the late 1980s, suggest that this may be the result of the misinterpretation of the evidence and a poor understanding of the mechanisms that cause and sustain the degradation of the land. The additional research required to resolve that situation will further slow direct action against desertification, but it may be the price that has to be paid to ensure future success.

## DROUGHT PREDICTION

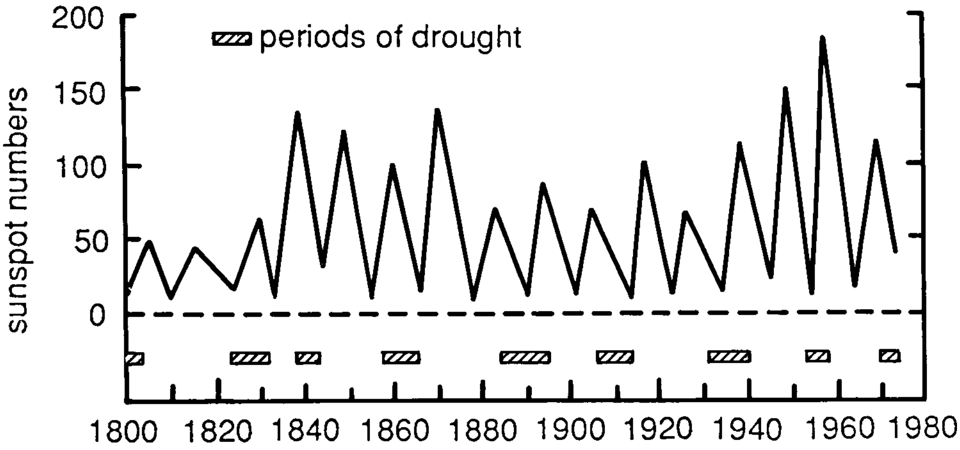
Even if all of these methods of dealing with drought, famine and desertification were to be initiated immediately, the results would be a long time coming. In Africa, this means that the existing and recurring problems of drought and famine must receive continuing and immediate attention. To be effective such aid requires an early warning of the problem, fast response and timely delivery of relief. The last two are essentially socio-economic elements, but the first is physical and it has led to numerous attempts by climatologists in recent years to devise a method by which drought may be predicted.

Drought is not the sole cause of famine or desertification, but it is certainly a major cause, often initiating the problem only to have it intensified by other factors. Prevention of drought is not feasible at present, nor would it necessarily bring about an end to famine and desertification if it was. If drought could be predicted, however, responses could be planned, and the consequences therefore much reduced. The simplest approach is the actuarial forecast, which estimates the probability of future drought based on past occurrences. To be successful, actuarial forecasting requires a lengthy sequence of data for analysis (Schneider 1978). In many areas, including sub-Saharan Africa, the record is simply too short to provide a reliable prediction. Problems with the homogeneity of the meteorological record may also reduce the significance of the results.

An extension of the actuarial approach is the linking of meteorological variables with some other environmental variable which includes a recognized periodicity in its behaviour (Oguntoyinbo 1986). One of the most commonly cited links of this type is the relationship between sunspot activity and precipitation (see Figure 3.13). In North America, drought on the plains has been correlated with the minimum of the 22-year double sunspot cycle. The drought years of the mid-1970s, for example, coincided with a period of minimum sunspot activity. The previous drought, some 20 years earlier, in the mid-1950s, also fitted into the cycle. Close as such a correlation may seem, it applies less well outside the western United States. Furthermore, the relationship remains a statistical one, and, as Schneider (1978) has pointed out, there is no physical theory to explain the connection between the two phenomena.

In the search for improved techniques of

*Figure 3.13* Drought and sunspot cycles in western North America

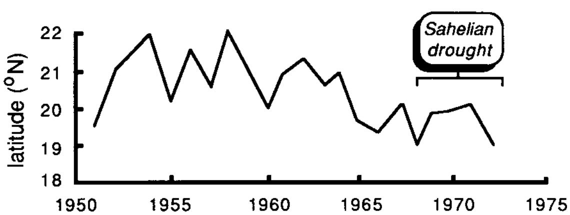



*Source:* After Schneider and Mtesirow (1976), Lockwood (1979)

drought prediction much time and effort has gone into the study of the physical causes of drought. The immediate causes commonly involve changes in atmospheric circulation patterns. Drought in the western prairies of Canada and the United States, for example, is promoted by a strong zonal airflow, which brings mild Pacific air across the western mountains. As it flows down the eastern slopes, it warms up, and its relative humidity decreases, causing the mild, dry conditions in winter and the hot, dry conditions in summer, which produce drought (Sweeney 1985). Seasonal drought in the Sahel was long linked to the failure of the ITCZ to move as far north as normal during the northern summer (see Figure 3.14). This is no longer generally accepted as sufficient to explain the lengthier dry spells, however, and the Sahelian drought is now being examined as part of the broader pattern of continent-wide rainfall variability, associated with large-scale variations in the atmospheric circulation (Nicholson 1989).

This type of knowledge is, in itself, of limited help in predicting or coping with drought, since, by the time the patterns are recognized, the drought has already arrived. It is necessary to move back a stage to try to find out what caused the circulation change in the first place. Over North America, for example, circulation patterns seem to be related to changing sea surface temperatures in the North Pacific, which cause the course of the upper westerlies to be altered, creating a zonal flow across the continent. The failure of the ITCZ to move as far north as normal into the Sahel has also been linked to a strengthening of the westerlies in the northern hemisphere. This prevents the poleward migration of the sub-tropical anticyclone lying over the Sahara, and it remains in place to block the rain-bearing winds which would normally flow over the area from the Atlantic (Bryson 1973). The drought in Africa has also been

*Figure 3.14* Variations in the northward penetration of the monsoon rains in the Sahel 1950–72




*Source:* After Bryson and Murray (1977) blamed on the intensification of the tropical Hadley cell. The descending arm of that cell is responsible for the general aridity in the region, and any increase in its strength or extent is accompanied by further suppression of precipitation, particularly in areas peripheral to the desert. The synchronicity of wet and dry years, north and south of the Sahara, supports this explanation (Nicholson 1981).

It has also been suggested that human activities have caused 'degradation induced drought' by contributing to the process by which the Hadley cell is intensified. Charney (1975) proposed that overgrazing and wood cutting, in the Sahel, increased the surface albedo, and disrupted the regional radiation balance. Surface heating declined as more solar radiation was reflected, and this in turn caused some cooling of the atmosphere. This cooling encouraged subsidence, or augmented existing subsidence, and helped to reduce the likelihood of precipitation by retarding convective activity. With less precipitation, vegetation cover decreased, and the albedo of the surface was further enhanced. This process was described as a biogeophysical feedback mechanism. It received considerable attention in the 1980s because it seemed to fit the observation that drought in the Sahel was more persistent than elsewhere in Africa. While such persistence may appear to be a function of the positive feedback mechanism central to the theory, it cannot be taken as confirmation of it (Hulme 1989).

As with many of the efforts to explain drought in Africa, it was difficult to develop the theory of degradation-induced drought further, because of the lack of empirical evidence. Following a study of long-term changes in African rainfall, Nicholson (1989) concluded that the human cause of drought, as espoused by Charney, did not seem feasible, but allowed that surface changes—whatever the cause—might feed back into the system to reinforce the drought. Establishing the nature and extent of these surface changes has not been easy. The most obvious approach would be the use of satellite remote sensing to estimate both vegetation destruction and changes in the surface albedo. However, the controversy over the interpretation of satellite data in assessing the extent of desertification has yet to be resolved, and problems still remain in the use of satellite derived data in this type of modelling (Thomas and Henderson-Sellers 1987). The existing data record is also short. Hulme (1989), in his assessment of the theory, estimated that changes of the magnitude proposed by Charney—a 14 to 35 per cent increase in albedo—would require vegetation destruction on at least a sub-continental scale over a period of as much as 20 years. As yet there is no evidence of this, but that may be in part a function of the inadequacy of the data, and he concluded that the theory is at best 'not proven'. Since then, Balling (1991) has calculated that desertification may actually have caused surface air temperatures to increase (rather than decrease as Charney's theory requires), although Hulme and Kelly (1993) have suggested that Balling's estimates of warming are too high.

While such studies may ultimately provide a better understanding of the problems of drought, and the mechanisms involved, they are insufficient to provide a direct forecasting mechanism. Researchers have re-examined certain relationships in the earth/atmosphere system in search of something more suitable. Their approach is based on the observation that the various units in the system are interconnected in such a way that changes in one unit will automatically set in motion changes in others, through autovariation. Since many of the changes are time-lagged, it should be possible to predict subsequent developments if the original change can be recognized. This forms the basis of the concept of teleconnection, or the linking of environmental events in time and place.

In recent years the search for a drought forecasting mechanism involving teleconnection has centred on changing conditions in the world's oceans. Sea-surface temperatures (SSTs) have been examined as possible precursors of the circulation patterns which cause drought in the Sahel, and a correlation between global SSTs and drought has been established (Folland *et al.* 1986; Owen and Ward 1989). When southern hemisphere ocean temperatures exceed those in the northern hemisphere, rainfall in the Sahel is below average. The warmer southern oceans may reduce the strenghth of the ITCZ leading to less uplift and therefore less precipitation. When the world began warming in the 1980s, the southern oceans warmed first and fastest, and the years with record global temperatures—1983, 1987 and 1990—were also years in which the rains failed. Only 1988 did not fit the pattern, and Pearce (1991b) has drawn attention to the possibility that if global warming continues as expected, drought in the Sahel might only get worse.

The links established between SSTs and drought in sub-Saharan Africa have allowed the UK Meteorological Office, through the Hadley Centre for Prediction and Research, to issue rainfall forecasts for the area (Owen and Ward 1989). These involve multi-stage predictions. To be useful, the forecasts have to be supplied by April, but it is the SSTs in June and July that correlate most closely with the rainfall. Thus the precipitation forecast is based on SSTs predicted two months ahead, and any changes between April and June will reduce the quality of the forecast. Apart from 1988, when a strong La Niña caused a major cooling of the tropical Pacific and ruined the forecast, the predictions have been remarkably accurate (Pearce 1991b). Although the lead time is short, the approach is one of the most promising yet developed for drought prediction.

ENSO events in the south Pacific have also received considerable attention as potential precursors of drought. It has long been known that following an El Niño changes occur in wind fields, sea surface temperatures and ocean circulation patterns. The large shifts of air and water, associated with these developments, cause major alterations to energy distribution patterns. Zonal energy flow replaces the meridional flow which is normal in tropical Hadley cells, and, because of the integrated nature of the atmospheric circulation, the effects are eventually felt beyond the tropics. Reduced rainfall has been noted in a number of semi-arid areas following such episodes and teleconnections have been established between ENSO events and precipitation in areas as far apart as Brazil, India, Indonesia and Australia. Drought in north-eastern Brazil commonly occurs in conjunction with an El Niño event, and India receives less monsoon rainfall during El Niño years. The relationship is well-marked in India, where monsoon rainfall over most of the country was below normal in all of the 22 El Niño years between 1871 and 1978 (Mooley and Parthasarathy 1983). Similarly, in Australia 74 per cent of the El Niño events between 1885 and 1984 were associated with drought in some part of the interior of the continent (Heathcote 1987). Such figures suggest the possibility of El Niño episodes being used for drought prediction in some parts of the world.

There is no clear relationship between drought in the Sahel and the occurrence of ENSO events (Lockwood 1986). Semazzi *et al.* (1988) have suggested that sub-Saharan rainfall is linked to ENSO events through the influence of the latter on SSTs in the Atlantic. However, SST anomalies do occur in years when El Niños are poorly developed or absent. Thus, although an ENSO episode may be a contributory factor in the development of drought in the Sahel, it does not seem to be a prerequisite for that development. Associated with ENSO is La Niña, which has physical characteristics completely opposite to those of El Niño. It is a cold current rather than a warm one and flows west instead of east. The climatological impact of La Niña also seems to be opposite to that of El Niño. At the time of the last major La Niña—in 1988—heavy rain caused flooding in Bangladesh, Sudan and Nigeria. The drought forecast for the Sahel that year did not come to pass. Instead, the region experienced one of its wettest years in recent decades (Pearce 1991b). There is as yet too little data to establish a link between La Niña and rainfall variability, but it is a relationship that merits additional investigation.

Teleconnection links remain largely

theoretical, although most of the relationships can be shown to be statistically significant. Certainly, in the study of drougmht, it has not been possible to establish physical relationships which would allow increasing aridity to be predicted with any accuracy. However, it seems probable that future developments in drought prediction will include consideration of teleconnections, particularly those involving time-lags, established in conjunction with the improvement of general circulation models (Oguntoyinbo 1986).

## SUMMARY

In many parts of the world, low precipitation levels combine with high evapotranspiration rates, to produce an environment characterized by its aridity. Under natural conditions, the ecological elements in such areas are in balance with each other and with the low moisture levels. If these change, there is a wholesale readjustment as the environment attempts to attain balance again. The early inhabitants of these areas also had to respond to the changes, and, as long as their numbers remained small and their way of life nomadic, they coped remarkably well. As human activities became more varied and technologically more sophisticated, as the way of life became more sedentary, and populations increased, the stage was set for problems with aridity. Environmentally appropriate responses to aridity were no longer possible, and the effects of drought were magnified. The failure of crops and the decimation of flocks and herds caused starvation and death. In some areas, the combination of drought and unsuitable agricultural practices created desert-like conditions.

Many of the problems associated with drought, famine and desertification stem from humankind's inability to live within the constraints of an arid environment, and one solution would be to restrict activities in drought-prone regions. Given existing political, cultural and socio-economic realities, such an approach is not feasible in most of the affected areas. Unfortunately, many of the alternative solutions are short-term in their impact—of necessity in many cases—and, in some areas at least, may be setting up even greater difficulties in the years to come. In short, solutions to the problems of drought, famine and desertification are unlikely to be widely available in the foreseeable future, and the images generated throughout sub-Saharan Africa in the last two decades are likely to recur with sickening frequency.

## SUGGESTIONS FOR FURTHER READING

Mortimer, M. (1989) *Adapting to Drought: Farmers, Famines and Desertification in West Africa,* Cambridge, Cambridge University Press.

Royal Meteorological Society (1989) 'Special Africa Issue': *Weather,* 44(2):, London: Royal Meteorological Society.

Steinbeck, J. (1958) *The Grapes of Wrath,* New York: Viking Press.

UNCOD (1977) *Desertification: Its Causes and Consequences,* Oxford: Pergamon Press.

# 4

# Acid rain

The unrelenting pollution of the atmosphere by modern society is at the root of several global environmental issues. The emission of pollutants into the atmosphere is one of the oldest human activities, and the present problems are only the most recent in a lengthy continuum. Issues such as acid rain, increased atmospheric turbidity and the depletion of the ozone layer, include essentially the same processes which led to the urban air pollution episodes of a decade or two ago. The main difference is one of scale. The previous problems had a local, or at most, a regional impact. The current issues are global in scope, and therefore potentially more threatening.

## THE NATURE AND DEVELOPMENT OF ACID RAIN

Acid rain is normally considered to be a by-product of modern atmospheric pollution. Even in a pure, uncontaminated world, however, it is likely that the rainfall would be acidic. The absorption of carbon dioxide by atmospheric water produces weak carbonic acid, and nitric acid may be created during thunderstorms, which provide sufficient energy for the synthesis of oxides of nitrogen ($NO_X$) from atmospheric oxygen and nitrogen. During volcanic eruptions or forest fires, sulphur dioxide ($SO_2$) is released into the atmosphere to provide the essential component for the creation of sulphuric acid. Phytoplankton in the oceans also emit sulphur during their seasonal bloom period. The sulphur takes the form of dimethyl sulphide (DMS) which is oxidized into $SO_2$ and methane sulphonic acid (MSA). The MSA is ultimately converted into sulphate (Cocks and Kallend 1988). Acids formed in this way fall out of the atmosphere in rain to become involved in a variety of physical and biological processes once they reach the earth's surface. The return of nitrogen and sulphur to the soil in naturally acid rain helps to maintain nutrient levels, for example. The peculiar landscapes of limestone areas—characterized by highly weathered bedrock, rivers flowing in steep-sided gorges or through inter-connected systems of under-ground stream channels and caves—provide excellent examples of what even moderately acid rain can do.

In reality, since 'acid rain' includes snow, hail and fog as well as rain, it would be more appropriate to describe it as 'acid precipitation'. The term 'acid rain' is most commonly used for all types of 'wet deposition', however. A related process is 'dry deposition', which involves the fallout of the oxides of sulphur and nitrogen from the atmosphere, either as dry gases or adsorbed on other aerosols such as soot or fly ash (Park 1987). As much as two-thirds of the acid precipitation over Britain falls as dry deposition in the form of gases and small particles (Mason 1990). On contact with moisture in the form of fog, dew or surface water they produce the same effects as the constituents of wet deposition. At present, both wet and dry deposition are normally included in the term 'acid rain' and, to maintain continuity, that convention will be followed here.

Current concern over acid rain is not with the naturally produced variety, but rather with that which results from modern industrial activity. Technological advancement in a society often depends upon the availability of metallic ores, which can be smelted to produce the great volume and variety of metals needed for industrial and socio-economic development. Considerable amounts of $SO_2$ are released into the atmosphere as a by-product of the smelting process, particularly when non-ferrous ores are involved. The burning of coal and oil, to provide energy for space heating or to fuel thermal electric power stations, also produces $SO_2$. The continuing growth of transportation systems using the internal combustion engine—another characteristic of a modern technological society—contributes to acid rain through the release of $NO_X$ into the atmosphere.

Initially, the effects of these pollutants were restricted to the local areas in which they originated, and where their impact was often obvious. The detrimental effects of $SO_2$ on vegetation around the smelters at Sudbury (Ontario), Trail (British Columbia), Anaconda (Montana) and Sheffield (England) have long been recognized, for example (Garnett 1967; Hepting 1971). As emissions increased, and the gases were gradually incorporated into the larger scale atmospheric circulation, the stage was set for an intensification of the problem. Sulphur compounds of anthropogenic origin are now blamed for as much as 65 per cent of the acid rain in eastern North America, with nitrogen compounds accounting for the remainder (Ontario: Ministry of the Environment 1980). In Europe, emission totals for $SO_2$ and $NO_X$ are commonly considered to split closer to 75 per cent and 25 per cent (Park 1987). Since the early 1970s, however, declining $SO_2$ emissions and a growing output of $NO_X$ have combined to bring

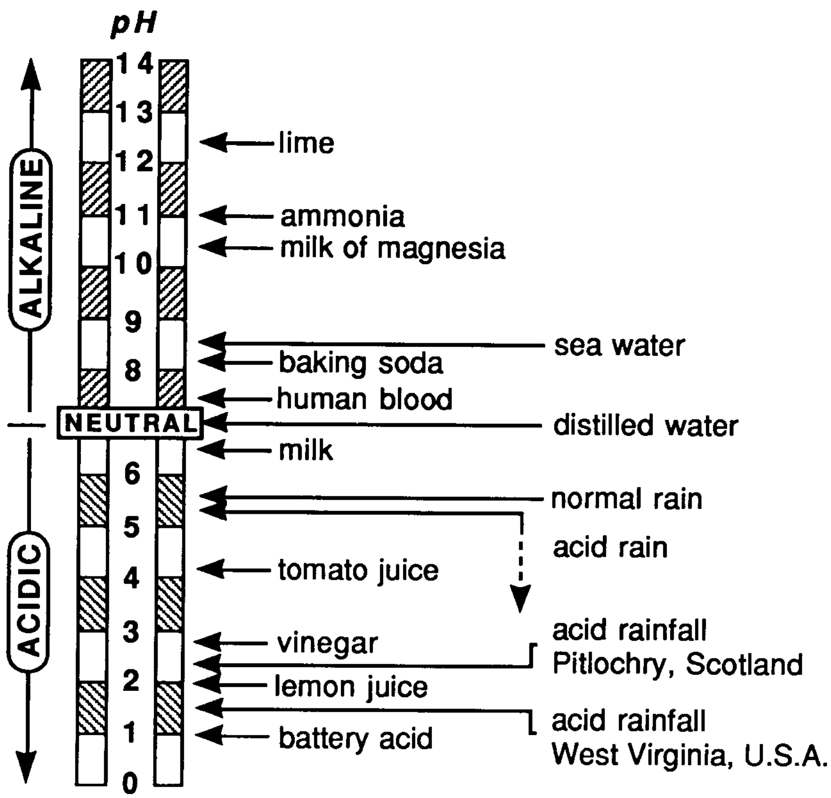
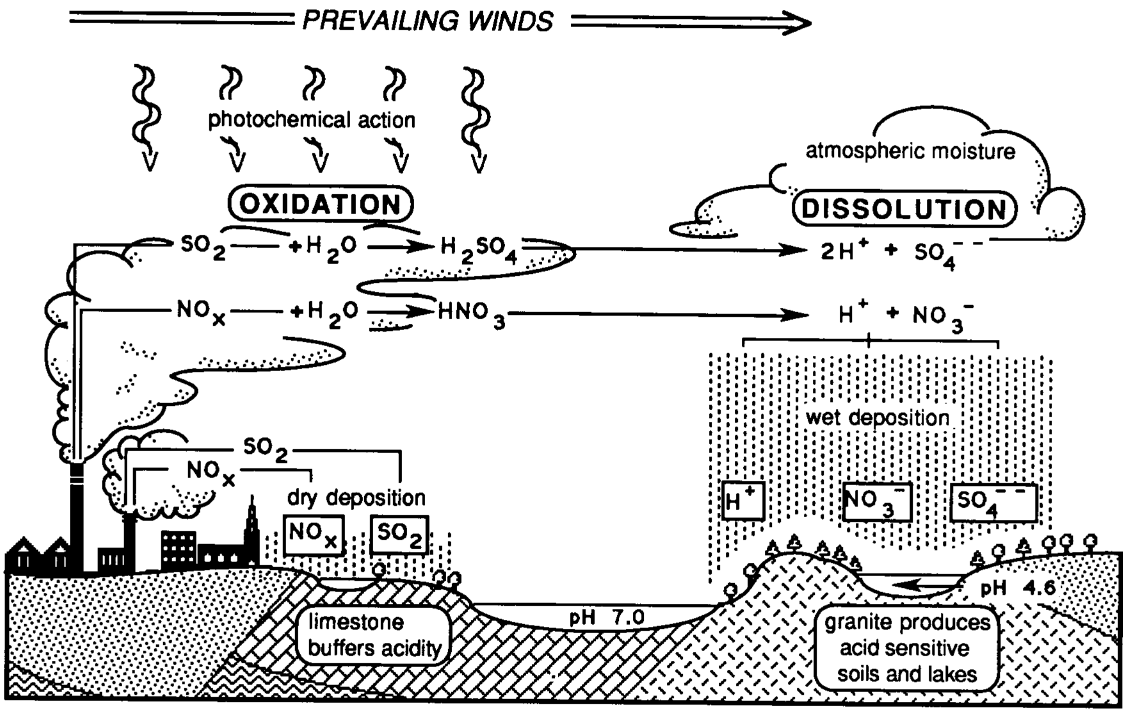



*Figure 4.1* The pH scale: showing the pH level of acid rain in comparison to that of other common substances

*Figure 4.2* Schematic representation of the formation, distribution and impact of acid rain




*Source:* Compiled from information in Park (1987); Miller (1984); LaBastille (1981)

the relative proportions of these gases close to the North American values (Mason 1990).

Acid precipitation produced by human activities differs from natural acid precipitation not only in its origins, but also in its quality. Anthropogenically produced acid rain tends to be many times more acidic than the natural variety, for example. The acidity of a solution is indicated by its hydrogen ion concentration or pH (potential hydrogen); the lower the pH, the higher the acidity. A chemically neutral solution, such as distilled water, has a value of 7, with increasingly alkaline solutions ranging from 7 to 14, and increasingly acidic solutions ranging from 7 down to 0 (see Figure 4.1). Since this pH scale is logarithmic, a change of one point represents a tenfold increase or decrease in the hydrogen ion concentration, while a two-point change represents a one hundredfold increase or decrease. A solution with a pH of 4.0 is ten times more acidic than one of pH 5.0; a solution of pH 3.0 is one hundred times more acidic than one of pH 5.0.

The difference between 'normal' and 'acid' rain is commonly of the order of 1.0 to 1.5 points. In North America, for example, naturally acid rain has a pH of about 5.6, whereas measurements of rain falling in southern Ontario, Canada, frequently provide values in the range of 4.5 to 4.0 (Ontario: Ministry of the Environment 1980). To put these values in perspective it should be noted that vinegar has a pH of 2.7 and milk a pH of 6.6 (see Figure 4.1). Thus, Ontario rain is about 100 times more acidic than milk, but 100 times less acidic than vinegar. Similar values for background levels of acidic rain are indicated by studies in Europe. The Central Electricity Generating Board (CEGB) in Britain has argued for pH 5.0 as the normal level for naturally acid rain (Park 1987), but the average annual pH of rain over Britain between 1978 and 1980 was between 4.5 and 4.2 (Mason 1990). Remarkably high levels of acidity have been recorded on a number of occasions on both sides of the Atlantic. In April 1974, for example, rain falling at Pitlochry, Scotland had a pH measured at 2.4 (Last and Nicholson 1982), and a value of 2.7 was reported from western Norway a few weeks later (Sage 1980). At Dorset, north of Toronto, Ontario, snow with a pH of 2.97 fell in the winter of 1976–77 (Howard and Perley 1991), and an extreme value of pH 1.5, some 11,000 times more acid than normal, was recorded for rain falling in West Virginia in 1979 (LaBastille 1981). Although these values are exceptional, the pattern is not. Acid deposition tends to be episodic, with a large proportion of the acidity at a particular site arriving in only a few days of heavy precipitation (Last 1989). Annual averages also mask large seasonal variations. Summer precipitation, for example, is often more acid than that in the winter, although emissions are generally less in the summer.

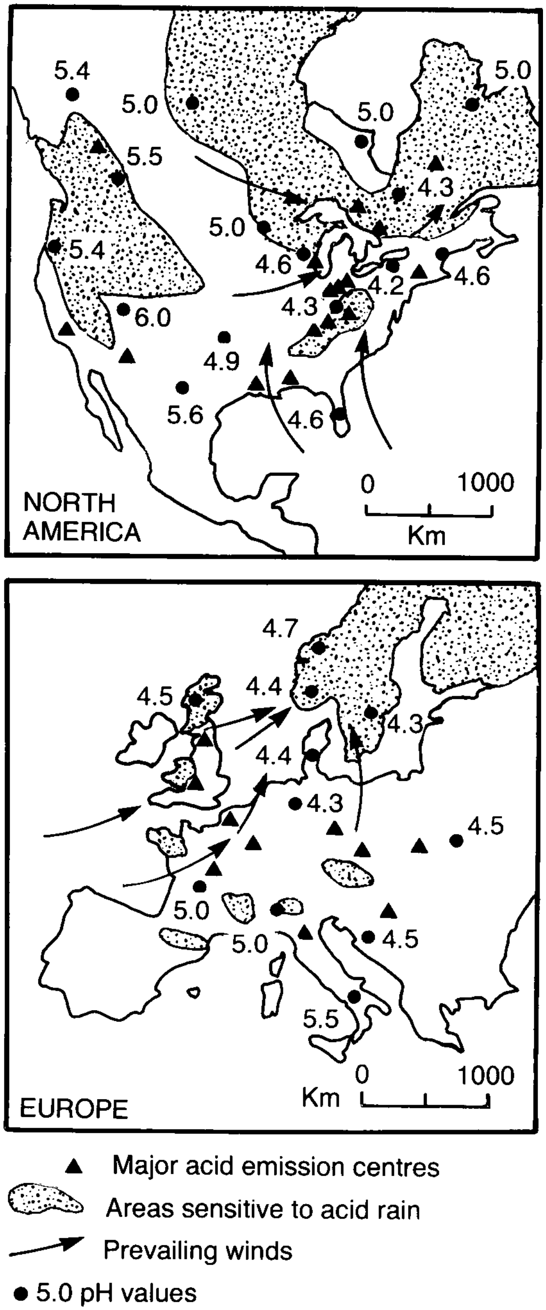
The quality of the rain is determined by a series of chemical processes set in motion when acidic materials are released into the atmosphere. Some of the $SO_2$ and $NO_X$ emitted will return to the surface quite quickly, and close to their source, as dry deposition. The remainder will be carried up into the atmosphere, to be converted into sulphuric and nitric acid, which will eventually return to earth as acid rain (see Figure 4.2). The processes involved are fundamentally simple. Oxidation converts the gases into acids, in either a gas or liquid phase reaction. The latter is more effective. The conversion of $SO_2$ into sulphuric acid in the gas phase is 16 per cent per hour in summer and 3 per cent per hour in winter. Equivalent conversion rates in the liquid phase are 100 per cent per hour in summer and 20 per cent per hour in winter (Mason 1990). Despite the relatively slow conversion to acid in the gas phase, it is the main source of acid rain when clouds and rain are absent, or when humidity is low.

The rate at which the chemical reactions take place will also depend upon such variables as the concentration of heavy metals in the airborne particulate matter, the presence of ammonia and the intensity of sunlight. Airborne particles of manganese and iron, for example, act as catalysts to speed up the conversion of $SO_2$ to sulphuric acid and sulphates. Natural ammonia may have similar effects (Ontario: Ministry of the Environment 1980). Sunshine provides the energy for the production of photo-oxidants—such as ozone ($O_3$), hydrogen peroxide ($H_2O_2$) and the hydroxyl radical (OH)—from other pollutants in the atmosphere, and these oxygen-rich compounds facilitate the oxidation of $SO_2$ and the $NO_X$ to sulphuric and nitric acid respectively (Cocks and Kallend 1988). The role of the photochemical component in the conversion process may account for the greater acidity of summer rainfall in many areas (Mason 1990). In the presence of water, these acids, and the other chemicals in the atmosphere, will dissociate into positively or negatively charged particles called ions. For example, sulphuric acid in solution is a mixture of positively charged hydrogen ions (cations) and negatively charged sulphate ions (anions). It is these solutions, or 'cocktails of ions', as Park (1987) calls them, that constitute acid rain.

Whatever the complexities involved in the formation of acid rain, the time scale is crucial. The longer the original emissions remain in the atmosphere, the more likely it is that the reactions will be completed, and the sulphuric and nitric acids produced. Long Range Transportation of Atmospheric Pollution (LRTAP)—transportation in excess of 500 km—is one of the mechanisms by which this is accomplished.

Air pollution remained mainly a local problem in the past. The effects were greatest in the immediate vicinity of the sources, and much of the effort of environmental groups in the 1960s and 1970s was expended in attempts to change that situation. Unfortunately, some of the changes inadvertently contributed to the problem of acid rain. One such was the tall stacks policy. In an attempt to achieve the reduction in ground level pollution required by the Clean Air Acts, the CEGB in Britain erected 200 m high smokestacks at its generating stations (Pearce 1982d). Industrial plants and power stations in the United States took a similar approach, increasing the heights of their stacks until, by 1977 more than 160 were over 150 m high (Howard and Perley 1991) and by 1981, at least 20 were more than 300 m high (LaBastille 1981). The International Nickle Company (INCO) added a 400 m superstack to its nickel smelter complex at Sudbury, Ontario in 1972 (Sage 1980). The introduction of these taller smokestacks on smelters and thermal electric power stations, along with the higher exit velocities of the emissions, allowed the pollutants to be pushed higher into the atmosphere. This effectively reduced local pollution concentrations, but caused the pollutants to remain in the atmosphere for longer periods of time, thus increasing the probability that the acid conversion processes would be completed. The release of pollutants at greater altitudes also placed them outside the boundary layer circulation and into the larger scale atmospheric circulation system with its potential for much greater dispersal through the mechanisms of LRTAP. The net result was a significant increase in the geographical extent of the problem of acid rain.

*Figure 4.3* The geography of acid rain in Europe and North America

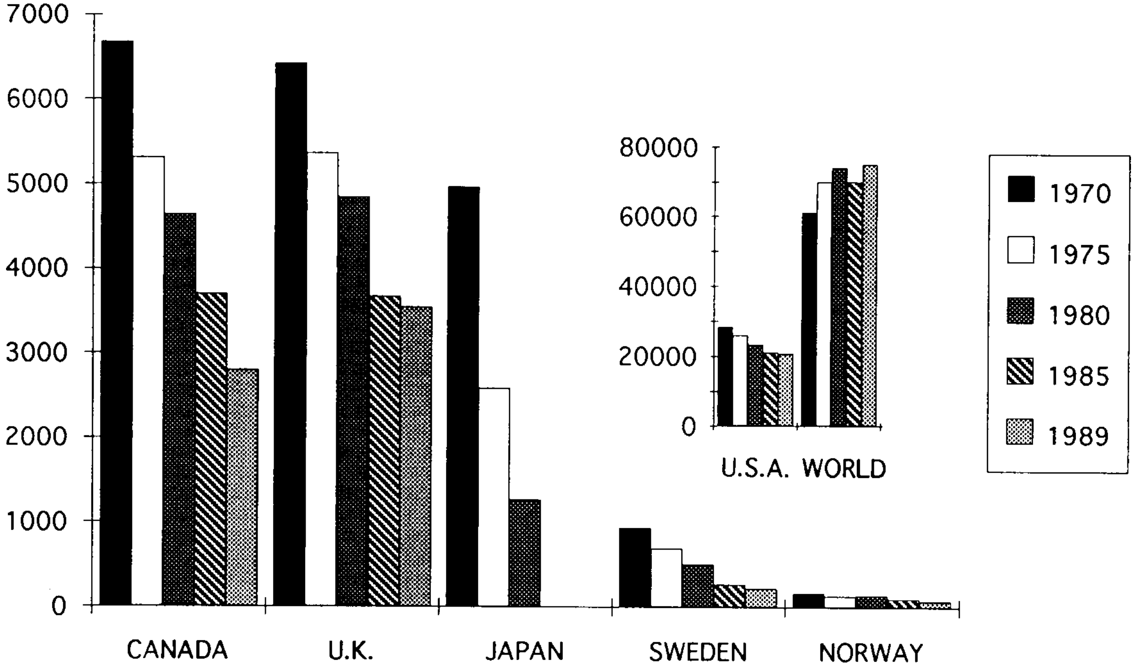



*Source.* Compiled from data in Park (1987); Miller (1984);
LaBastille (1981); Ontario: Ministry of the Environment (1980)

## THE GEOGRAPHY OF ACID RAIN

Total global emissions of the $SO_2$ and $NO_X$, the main ingredients of acid rain, are difficult to estimate. Fossil fuel combustion alone produces about 91 million tonnes annually (Hameed and Dignon 1992) and other activities, both natural and anthropogenic, add to that. The main sources are to be found in the industrialized areas of the northern hemisphere. Northeastern North America, Britain and western Europe have received most attention (see Figure 4.3), but eastern Europe and the republics of the former USSR—Russia, Ukraine and Kazakhstan along with eastern and western Europe, emit a—are also important sources. These republics, combined total of some 54 million tonnes of $SO_2$

*Figure 4.4* Sulphur dioxide emissions in selected countries: 1970–89

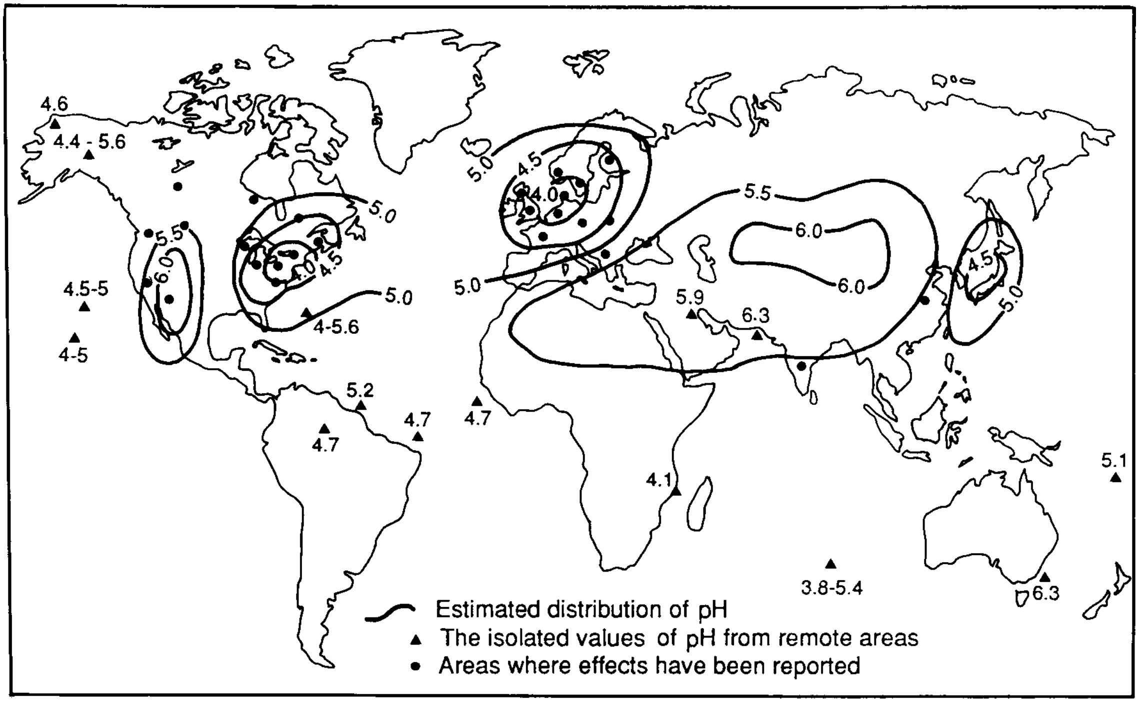



*Source:* Based on data in World Resources Institute (1992)

every year, or almost double that produced in North America (Barrie 1986). In Asia, Japanese industries emit large quantities of $SO_2$ (Park 1987), while the industrial areas of China are also major contributors. Annual emissions of $SO_2$ in China average 15 million tonnes, but have been as high as 24 million tonnes (Glaeser 1990).

Sulphur dioxide emission levels in the western industrialized nations peaked in the mid-1970s or early 1980s, and have declined significantly since then (see Figure 4.4). In Britain, for example, the output of $SO_2$ decreased by 35 per cent between 1974 and 1990 (Mason 1990). Similar declines in $SO_2$ have been recorded for North America and western Europe, and that trend is likely to continue as new environmental regulations are introduced and enforced. In contrast, emissions of $NO_X$ continue to rise. This may be due in part to increased automobile traffic, but it also reflects the limited attention given to $NO_X$ reduction in most acid pollution control programmes. The trends are less clear and more difficult to forecast outside western Europe and North America. As long as the economic and political disarray continues in eastern Europe and the former Soviet Union, it is unlikely that pollution control programmes will be given top priority, and acid gas emissions are likely to remain high or even increase. Chinese economic development will continue to be fuelled by low-quality, sulphur-rich coal, leading to increased local and regional levels of atmospheric acidity (Glaeser 1990). In contrast, Japan—the leading industrial nation in Asia—was quick to install pollution control equipment to reduce $SO_2$ and $NO_X$ levels in the 1980s (Ridley 1993), and the decline in emissions there is likely to continue. The problem of acid rain has received less attention in Asia than in Europe or North America, but a new study initiated in 1992 under

*Figure 4.5* The geography of acid rain, showing areas with pH below 5.0



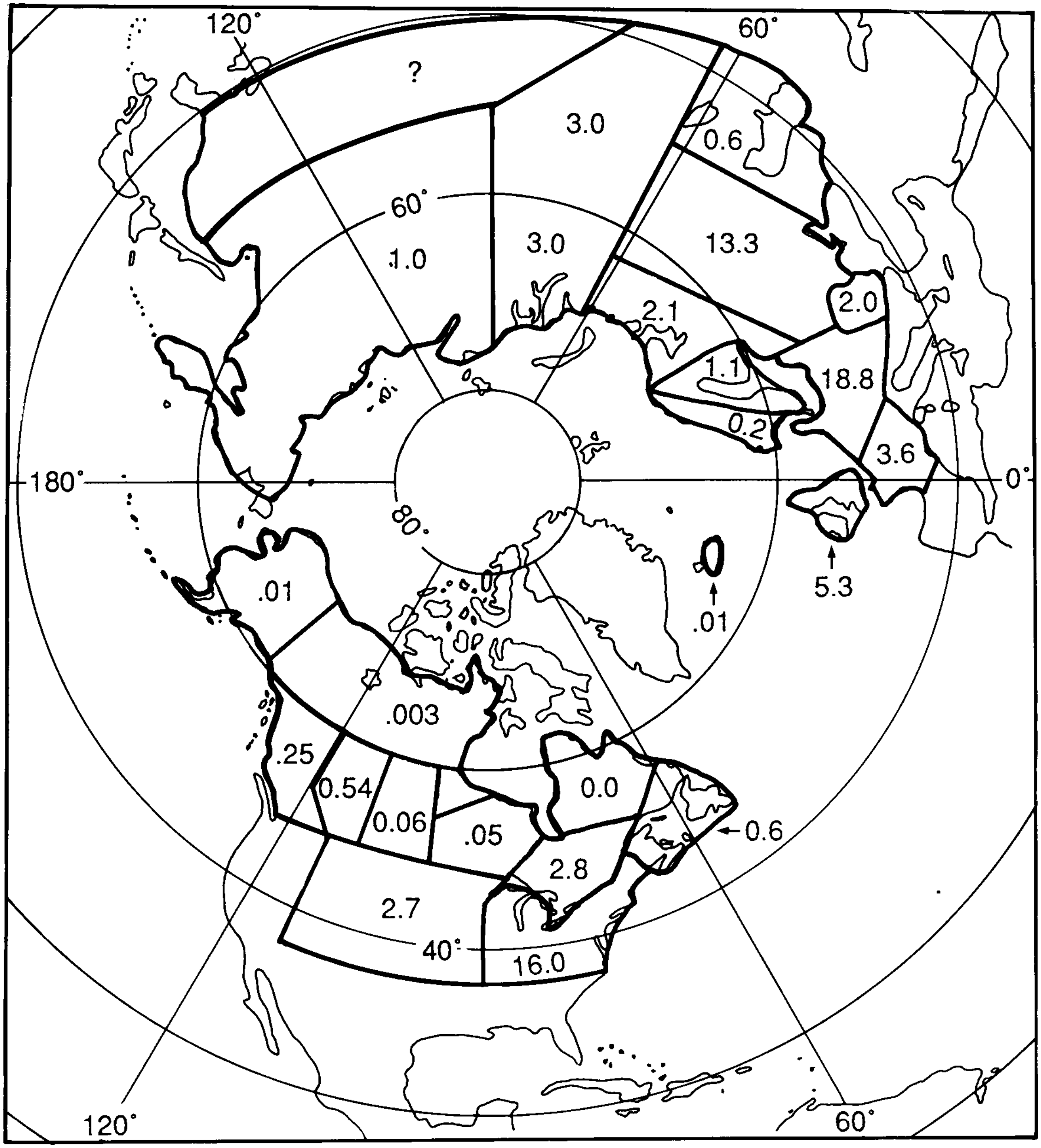

*Source:* After Park (1991)

the auspices of the World Bank has been designed to change that. The study will be based on a computer model called RAINS similar to one developed by the International Institute for Applied Systems Analysis for the European Community. Results from the model will allow researchers to alert Asian governments to the extent and intensity of the acid rain problem, and to recommend ways of dealing with it (Hunt 1992).

Acid emissions remain limited outside the major industrial nations, but concern has been expressed over growing levels of air pollution which may already have provided a base for acid rain in some Third World countries (Park 1987). The future extent of the problem will depend upon the rate at which these countries industrialize, and the nature of that industrialization. Experience in the developed world shows that other possibilities exist also. For example, large conurbations—such as Los Angeles—with few sulphur producing industries, but with large volumes of vehicular traffic, have been identified as sources of acidic pollution (Ellis *et al.* 1984). Many developing nations are becoming rapidly urbanized, and, as a result, may provide increased quantities of the ingredients of acid rain in the future (Pearce 1982c). Thus, although at present the geographical distribution of acid rain is largely restricted to the industrialized nations of the northern hemisphere, it has the potential to expand to a near-global scale in the future (see Figure 4.5).

All of the areas presently producing large amounts of acidic pollution lie within the mid-latitude westerly wind belt. Emissions from industrial activity are therefore normally carried eastwards, or perhaps northeastwards, often for several hundred kilometres before being redeposited. The distance and rate of travel are

*Figure 4.6* Annual emissions of sulphur dioxide ($10^6$ tonnes) in regions of the northern hemisphere that influence the Arctic




*Source:* From Barrie (1986)

closely linked to the height of emission. Pollution introduced into the upper westerlies or jet streams is taken further, and kept aloft longer, than that emitted into the boundary layer circulation. For example, a parcel of air tracked from Toronto, at an altitude of 5,000 m, was found well out over the Atlantic, some 950 km east of its source, in less than 12 hours. In the same time span, a parcel of air close to the surface covered less than a quarter of that distance (Cho *et al.* 1984). In this way pollutants originating in the US Midwest cause acid rain in Ontario, Quebec and the New England states; emissions from the smelters and power stations of the English Midlands and the Ruhr contribute to the acidity of precipitation in Scandinavia.

The ultimate example of LRTAP is provided by acidic pollution in the Arctic, which has been traced to sources some 8,000 km away in North America and Eurasia (Park 1987). The winter atmospheric circulation in high latitudes causes polluted air to be drawn into the Arctic air mass in sufficient quantity to reduce visibility—through the creation of Arctic haze (see Chapter 5)—and increase environmental acidity. Sulphur dioxide and sulphate particles are the main constituents of the pollution which originates in the industrial regions of Eurasia and North America, with the former contributing as much as 80 per cent of the total (see Figure 4.6). The net result at locations in the Canadian Arctic is an atmospheric sulphate content during the winter months which is at least twenty to thirty times that of the summer months (Barrie and Hoff 1985). Slightly higher winter concentrations have been recorded in the Norwegian and Russian Arctic (Barrie 1986). This seasonal variation is reflected in the acidity of the precipitation and the snowpack, which varies from a pH of about 5.6 in the summer to 4.9–5.2 in the winter months (Barrie 1986).

The problem of acid rain obviously transcends national boundaries, introducing political overtones to the problem, and creating the need for international co-operation, if a solution is to be found. That co-operation was not easily achieved. Since the ingredients of acid pollution are invisible, and the distances they are carried are so great, it is not possible to establish a visible link between the sources of the rain and the areas which suffer its effects. It was therefore easy for polluters to deny fault in the past. The introduction of airborne sampling systems, using balloons (LaBastille 1981), or aircraft (Pearce 1982d) has helped to change that. Tracer elements added to a polluted airstream or source-specific chemicals allow emissions from a particular area to be followed until they are deposited in acid rain (Fowler and Barr 1984). Mathematical models developed in Europe also allow the final destination of specific acid emissions to be identified (Cocks and Kallend 1988). With such developments in monitoring techniques, denial of guilt becomes more and more difficult.

## ACID RAIN AND GEOLOGY

The impact of acid rain on the environment depends not only on the level of acidity in the rain, but also on the nature of the environment itself. Areas underlain by granitic or quartzitic bedrock, for example, are particularly susceptible to damage, since the soils and water are already acidic, and lack the ability to 'buffer' or neutralize additional acidity from the precipitation. Acid levels therefore rise, the environmental balance is disturbed, and serious ecological damage is the inevitable result. In contrast, areas which are geologically basic—underlain by limestone or chalk for example—are much less sensitive, and may even benefit from the additional acidity. The highly alkaline soils and water of these areas ensure that the acid added to the environment by the rain is very effectively neutralized. In areas covered by glacial drift, or some other unconsolidated deposit, the susceptibility of the environment to damage by acid rain will be determined by the nature of the superficial material rather than by the composition of the bedrock. In theory, it is important to establish background levels of acidity or alkalinity, so that the vulnerability of the environment to acidification can be estimated; in reality, this is seldom possible, since, in most cases, environmental conditions had already been altered by acid rain, by the time monitoring was introduced.

The areas at greatest risk from acid rain in the northern hemisphere are the pre-Cambrian Shield areas of Canada and Scandinavia, where the acidity of the rocks is reflected in highly acidic soils and water. The folded mountain structures of eastern Canada and the United States, Scotland, Germany and Norway are also vulnerable (see Figure 4.3). Most of these areas have already suffered, but the potential for further damage is high. Should the present emission levels of $SO_2$ and $NO_X$ be maintained for the next ten to twenty years, it is likely that susceptible areas, presently little affected by acid rain—in western North America and the Arctic for example—would also suffer damage as the level of atmospheric acidity rises.

## ACID RAIN AND THE AQUATIC ENVIRONMENT

The earliest concerns over the impact of acid rain on the environment were expressed by Robert Smith, in England, as long ago as 1852 (Park 1987), but modern interest in the problem dates only from the 1960s. Initial attention concentrated on the impact of acid rain on the aquatic environment, which can be particularly sensitive to even moderate increases in acidity, and it was in the lakes and streams on both sides of the Atlantic that the effects were first apparent. Both LaBastille (1981) and Park (1987) credit Svente Oden, a Swedish soil scientist, with bringing the problem to the attention of the scientific community, in a campaign which began in 1963. Both also mention the work of Eville Gorham in the late 1950s, in the English Lake District, and the studies of Gene Likens and Herbert Bormann in New Hampshire, dating back to 1963. Gorham was also one of the first to become involved in the study of acid lakes in Canada, in the area polluted by smelter emissions around Sudbury, Ontario (Gorham and Gordon 1960). From these limited beginnings, the scientific investigation of the problem has grown rapidly. By the mid-1980s, a majority of scientists accepted that a link existed between the emissions of $SO_2$ and $NO_X$ and the acidification of lakes. A minority remained unconvinced. Along with politicians in the United States and Britain, they continued to counter requests for emission reductions with calls for more studies (Park 1987), despite an estimate that research over a quarter of a century had resulted in more than 3000 studies in North America alone (Israelson 1987).

There is a tendency for all lakes to become more acidic with time, as a result of natural ageing processes, but studies of acid-sensitive lakes suggest that observed rates of change in pH values since the middle of the nineteenth century have exceeded the expected natural rates. The analysis of acid sensitive diatom species in lake sediments has allowed pH-age profiles to be constructed for some 800 lakes in North America and Europe (Charles *et al.* 1990). Most of these profiles indicate that lake acidification is a relatively recent phenomenon, with little change in pH values indicated prior to 1850. In almost a century and a half since then, pH values in the lakes studied have decreased by between 0.5 and 1.5 units (see Figure 4.7). In contrast, less sensitive lakes—those with adequate buffering for example—showed little change.

Some of the increased acidity could be explained by changing land use. In the Netherlands, for example, agricultural practices such as sheep washing and the foddering of ducks kept levels of acidity artificially low in the past, but as these activities declined, the acidity of the lakes began to rise again (Charles *et al.* 1990). In south-west Scotland, reforestation has been accompanied by increasing acidity because the trees have a greater ability than the vegetation they replaced to scavenge acid aerosols from passing air streams (Mason 1990). Such situations seem to be the exception, however, and the general consensus is that declining pH values are the result of increased acidic deposition since the Industrial Revolution. Rising levels of copper, zinc and lead in the lake deposits, plus the

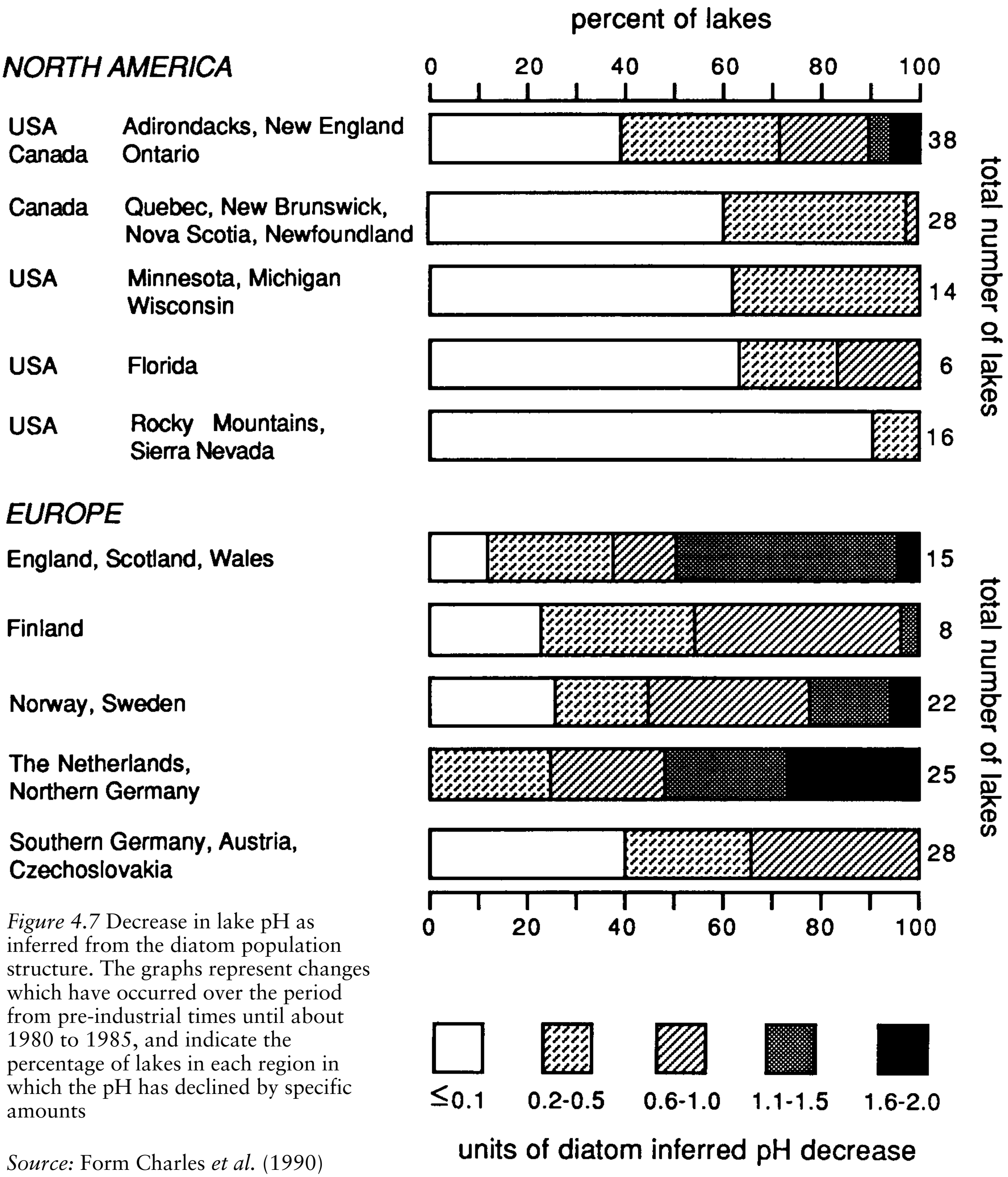
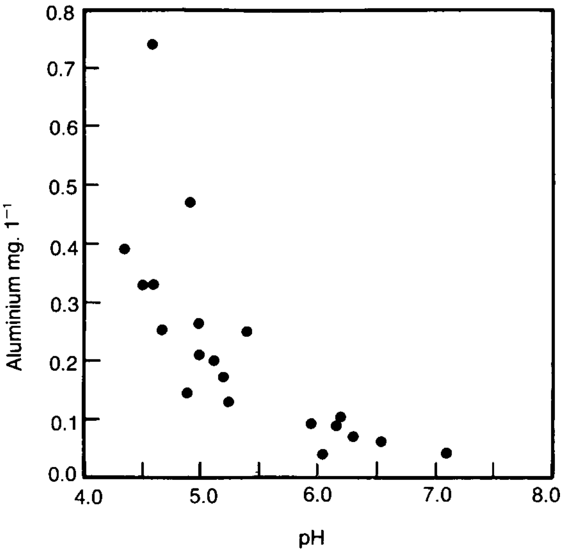



*Figure 4.7* Decrease in lake pH as inferred from the diatom population structure. The graphs represent changes which have occurred over the period from pre-industrial times until about 1980 to 1985, and indicate the percentage of lakes in each region in which the pH has declined by specific amounts

*Source:* Form Charles *et al.* (1990)

presence of soot from the burning of fossil fuels supports the industrial origin of the increased acidity (Last 1989). The corollary, that decreased acid emissions from industrial activities should lead to a reduction in lake acidity is perhaps reflected in rising pH values in some lakes in Britain and Scandinavia, but the data are as yet too limited to provide conclusive results (Last 1989; Mason 1990).

*Figure 4.8* Aluminium concentration in relation to pH for 20 lakes near Sudbury, Ontario




*Source:* From Harvey (1989)

Some uncertainties over the relationship between industrial emissions and acid rain will always remain, because of the complexity of the environment, and the variety of its possible responses to any input. There can be no doubt, however, that acid rain does fall, and when it does its effects on the environment are often detrimental.

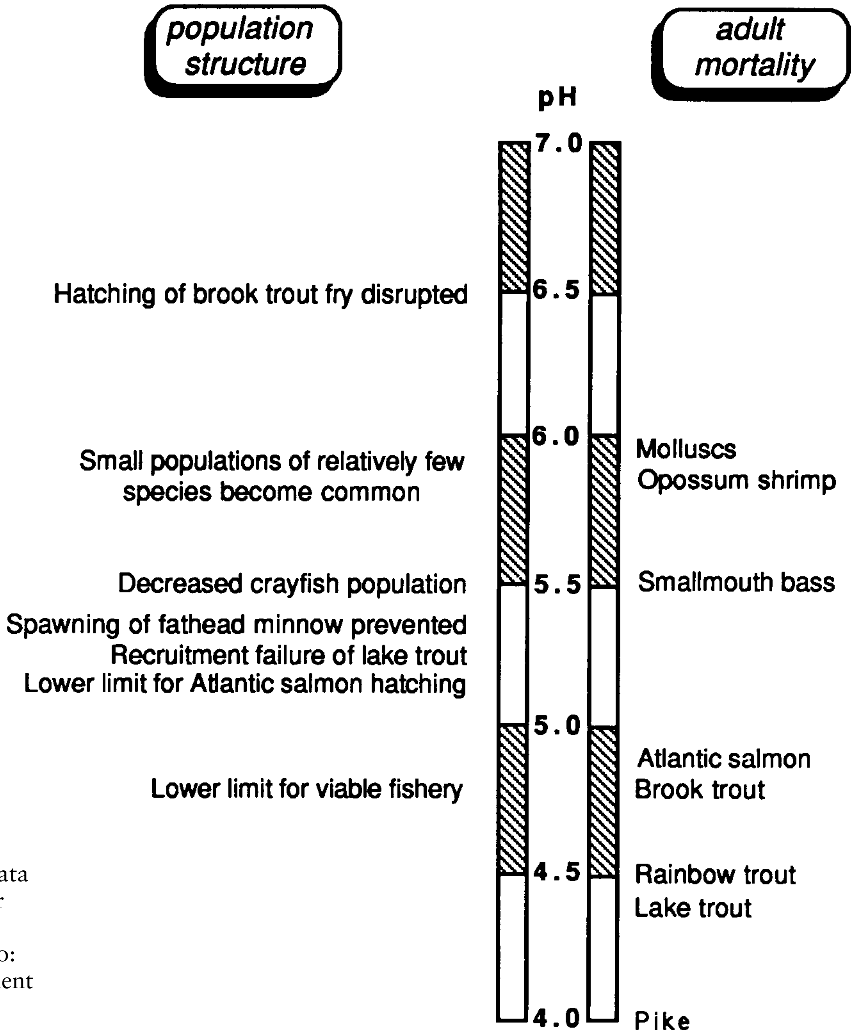
In addition to reduced pH values, acidic lakes are characterized by low levels of calcium and magnesium and elevated sulphate levels. They also have above-normal concentrations of potentially toxic metals such as aluminium (Brakke *et al.* 1988)(see Figure 4.8). The initial effect of continued acid loading varies from lake to lake, since waterbodies differ in their sensitivity to such inputs. Harmful effects will begin to be felt by most waterbodies when their pH falls to 5.3 (Henriksen and Brakke 1988), although damage to aquatic ecosystems will occur in some lakes before that level is reached, and some authorities consider pH 6.0 as a more appropriate value (Park 1987). Whatever the value, once the critical pH level has been passed, the net effect will be the gradual destruction of the biological communities in the ecosystem.

Most of the investigations into the impact of acid rain on aquatic communities have involved fish populations. There is clear evidence, from areas as far apart as New York State, Nova Scotia, Norway and Sweden, that increased surface water acidity has adverse effects on fish (Baker and Schofield 1985). The processes involved are complex and their effectiveness varies from species to species (see Figure 4.9). For example, direct exposure to acid water may damage some species. Brook trout and rainbow trout cannot tolerate pH levels much below 6.0 (Ontario: Ministry of the Environment 1980), and at 5.5 smallmouth bass succumb (LaBastille 1981). The *salmonid* group of fish is much less tolerant than coarser fish such as pike and perch (Ontario: Ministry of the Environment 1980). Thus as lakes become progressively more acid, the composition of the fish population changes.

The stage of development of the organism is also important (see Figure 4.10). Adult fish, for example, may be able to survive relatively low pH values, but newly hatched fry, or even the spawn itself, may be much less tolerant (Ontario: Ministry of the Environment 1980). As a result the fish population in acid lakes is usually wiped out by low reproductive rates even before the pH reaches levels which would kill mature fish (Jensen and Snekvik 1972).

Fish in acid lakes also succumb to toxic concentrations of metals, such as aluminium, mercury, manganese, zinc and lead, leached from the surrounding rocks by the acids. Many acid lakes, for example, have elevated concentrations of aluminium (Brakke *et al.* 1988), which has been recognized as a particularly potent toxin (Cronan and Schofield 1979). The toxic effects of aluminium are complex, but in lakes where the pH has fallen below 5.6 it is commonly present in sufficient quantity to kill fish (Stokes *et al.* 1989). The fish respond to the presence of the aluminium by producing mucus which clogs the gills, inhibiting breathing and causing a breakdown of their salt regulation systems

*Figure 4.9* The impact of acid rain on aquatic organisms

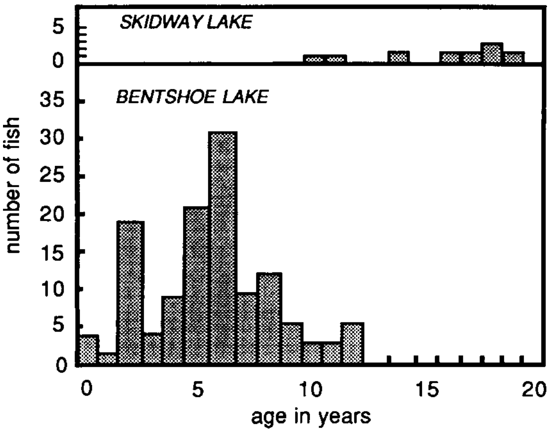



*Source:* Compiled from data in Israelson (1987); Baker and Schofield (1985); LaBastille (1981); Ontario: Ministry of the Environment (1980)

(Mason 1990). Aluminium also kills a variety of invertebrates, but the progressive concentration of the metal through food chains and food webs ensures that higher level organisms such as fish are particularly vulnerable, and it is possible that fish kills previously attributed to high acidity were, in fact, the result of aluminium poisoning (Park 1987). The mobilization of heavy metals by leaching may also help to reduce fish populations indirectly by killing the insects and microscopic aquatic organisms on which the fish feed. Birds such as herons, ospreys and kingfishers, which feed on the fish, and those such as ducks and other waterfowl, which depend upon molluscs and aquatic insects for their food, also feel the effects of this disruption of the food chain (Howard and Perley 1991).

The fish are particularly vulnerable during the annual spring flush of highly acidic water into the lakes and streams. This is a well-documented phenomenon which causes stress to all organisms in the aquatic environment (Park 1987). All of the areas presently affected by acid rain receive a proportion of their total precipitation in the form of snow. The acids falling in the snow during the winter accumulate on land and on the frozen

*Figure 4.10* The age-class composition of samples of the white sucker populations in lakes Skidway (pH 5.0) and Bentshoe (pH 5.9)




*Source:* From Harvey (1989)

waterways, until the spring melt occurs. At that time they are flushed into the system in concentrations many times higher than normal. Measurements in some Ontario lakes have shown a reduction in pH values of more than two units in a matter of a few days although decreases of the order of one pH unit are more common (Ontario: Ministry of the Environment 1980; Jeffries 1990). This augmented level of acidity may last for several weeks, and, unfortunately, it often coincides with the beginnings of the annual hatch. The recently hatched fry cannot survive the shock, and fish populations in acidic lakes often have reduced or missing age groups which reflect this high mortality (Baker and Schofield 1985). The aquatic ecosystems of lakes which are normally well-buffered are not immune to major damage if the melt is rapid and highly acidic (Ontario: Ministry of the Environment 1980).

Fish populations in many rivers and lakes in eastern North America, Britain and Scandinavia have declined noticeably in the last two to three decades, as a consequence of the effects of acid rain. Surveys of European and North American lakes have established that 50 per cent of lakes with a pH <5 are likely to contain no fish (Mason 1990). More than 300 lakes in Ontario, Canada, mainly in the vicinity of Sudbury, are fishless and many others have experienced a reduction in the variety of species they contain (Ontario: Ministry of the Environment 1980; Park 1991); several rivers in Nova Scotia, once famous for their Atlantic salmon, are now too acidic to support that fish (Israelson 1987). In the Adirondack Mountains of New York State between 200 and 400 lakes have lost some or all of their fish species (Harvey 1989). Damage to fish populations has occurred in an area of 33,000 sq km in southern Norway, with brown trout particularly hard hit (Baker and Schofield 1985). In nearby Sweden, 100 lakes sampled in the mid-1970s had already lost 43 per cent of their minnow, 32 per cent of their roach, 10 per cent of their arctic char and 14 per cent of their brown trout populations as a result of acidification (Almer *et al.* 1974), and by the end of the decade it was estimated that some 4,000 lakes in Sweden were fishless (LaBastille 1981). In Britain, no obvious problems emerged until the 1970s, when rivers and lakes in southwest Scotland, the English Lake District and Wales showed the first signs of decline in the numbers of trout, salmon and other game fish (Park 1987). Since then a number of studies have shown that the problem is particularly acute in those streams draining forested catchment areas, which are commonly more acidic. Many of these streams are completely devoid of fish, or support only a few species in their lower reaches, where the acidity is usually less (Elwood and Mulholland 1989).

Waterbodies which have lost, or are in the process of losing their fish populations are often described as ‘dead’ or ‘dying’. This is not strictly correct. All aquatic flora and fauna will decline in number and variety during progressive acidification, but, even at pH 3.5, water boatmen and whirligig beetles survive and multiply (LaBastille 1981), and species of protozoans are found at pH levels as low as 2.0 (Hendrey 1985). Phytoplankton will disappear when pH falls below 5.8 (Almer *et al.* 1974), but acid-tolerant

*Sphagnum* mosses will colonize the lake bottoms (Pearce 1982d). Rapid *Sphagnum* growth has been reported in Scandinavia, but in eastern North America large quantities of green algae are more common. The absence of insect larvae and other organisms which normally graze on the algae may in part explain its abundance (Stokes *et al.* 1989). Leaves or twigs falling into the water will be slow to decompose, because the bacteria which would normally promote decay have been killed by the acidic conditions (Park 1987). The absence of phytoplankton and the general reduction in organic activity allows greater light penetration, which makes acid lakes unnaturally clear and bluish in colour (LaBastille 1981). This ethereal appearance may suggest death, but even the most acid lakes have some life in them.

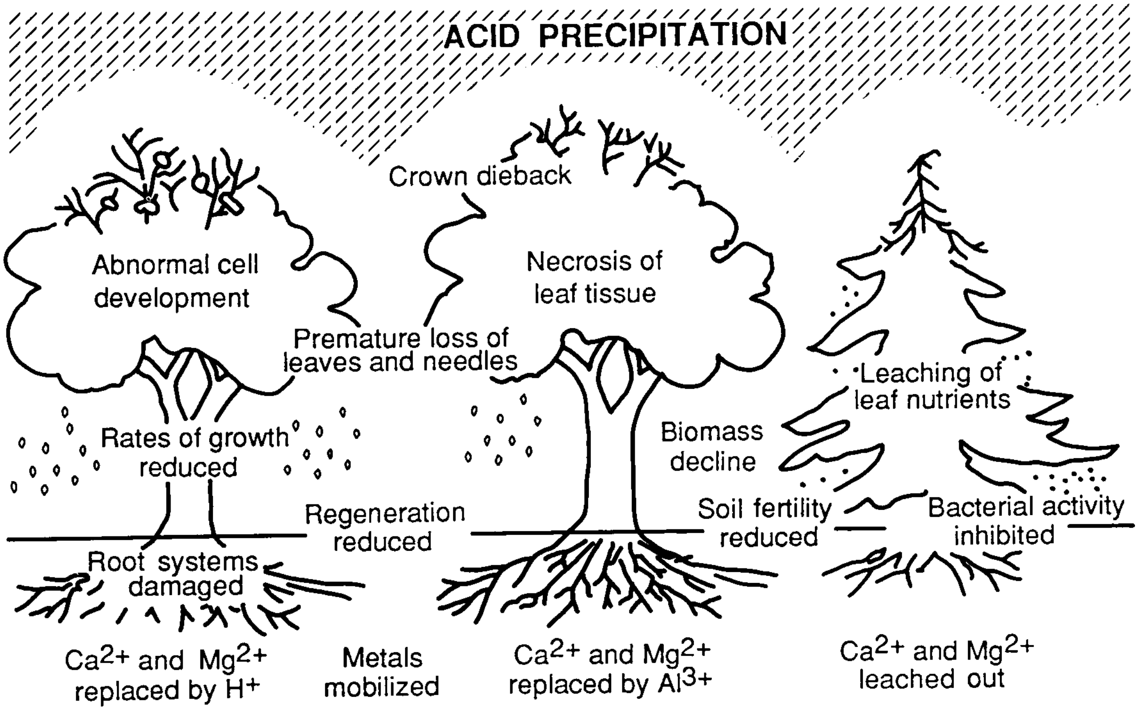
## ACID RAIN AND THE TERRESTRIAL ENVIRONMENT

Terrestrial ecosystems take much longer to show the effects of acid rain than aquatic ecosystems. As a result, the nature and magnitude of the impact of acid precipitation on the terrestrial environment has been recognized only recently. As early as 1965, however, air pollution was known to be killing oak and pine trees on Leo Tolstoy's historic estate at Yosnaya Polyana (Goldman 1971). There is growing evidence that those areas in which the waterbodies have already succumbed to acidification must also face the effects of increasing acid stress on their forests and soils. The threat is not universally recognized, however and there remains a great deal of controversy over the amount of damage directly attributable to acid rain. Reduction in forest growth in Sweden (LaBastille 1981), physical damage to trees in West Germany (Pearce 1982b), and the death of sugar maples in Quebec and Vermont (Norton 1985) have all been blamed on the increased acidity of the precipitation in these areas. Some of the soils developed on the hill-peats of Scotland appear to have become so acid that they can longer support the acid-tolerant heather native to the area (Last 1989). Although the relationship seems obvious in many cases, the growth, development and decline of plants has always reflected the integrated effects of many variables, including site microclimatology, hydrology, land-use change, age and species competition. Acid rain has now been added to that list. Even those individuals or groups with greatest concern for the problem admit that it is next to impossible to isolate the impact of any one element from such a combination of variables (Ontario: Ministry of the Environment 1980). Thus it may not be possible to establish definitive proof of the link between acid precipitation and vegetation damage. The body of circumstantial evidence is large, however, and adverse effects have been produced in laboratory experiments. Together, these support the view that the terrestrial environment is under some threat from acid rain.

Assessment of the threat is made difficult by the complexity of the relationships in the terrestrial environment. In areas experiencing acid rain, dry and wet deposition over land is intercepted initially by the vegetation growing there. The effects of this precipitation on the plants may be direct, brought about by the presence of acid particles on the leaves, for example, or indirect, associated with changes in the soil or the biological processes controlling plant growth (see Figure 4.11). Acid precipitation intercepted by trees may promote necrosis of leaf tissue, leaching of leaf nutrients and chlorophyll degradation (Shriner & Johnston 1985), all of which cause visible damage. Vegetation growing at high altitudes, and therefore enveloped in cloud for long periods, frequently displays such symptoms, since cloud moisture is often more acidic than rain (Hendrey 1985). Ultimately, the acid particles will be washed off the vegetation and into the soil, where they can begin to affect the plants indirectly, but no less seriously.

By intercepting acid deposition, plants, particularly trees, also act as concentrators. For example, dry deposition allowed to accumulate on the leaves or needles of the forest canopy, will increase the acidity of the rainfall which washes it out to the forest floor (Park 1987).

*Figure 4.11* The impact of acid rain on the terrestrial environment




*Source.* Compiled from data in Fernandez (1985); Shriner and Johnston (1985); Tomlinson (1985)

Episodic increases in acidity of this nature may be likened to the spring flush in the aquatic environment, although their intensity and duration is usually less.

Once the acid rain enters the soil, its impact will depend very much on the soil type and the underlying bedrock. Soils derived from granite, for example, will already be acidic, and therefore vulnerable to further increases. In contrast, soils developed over limestone, or some other calcium-rich source, will have the ability to neutralize large quantities of additional acid. Natural processes, such as the decay of organic matter or the weathering of minerals, increase the acidity of many soils, and it is often difficult to assess the contribution of acid rain to the total. Indeed, it has been argued that the addition of atmospheric acids may be relatively insignificant compared with those from in-soil processes (Krug and Frink 1983). The situation is further complicated when such soils are developed for agriculture. To maintain productivity, it is necessary to make regular applications of fertilizer and lime, which mask acidification.

Acidic water interferes with soil biology and soil chemistry, disturbing nutrient cycles and causing physiological damage to plant root systems. Increased acidity inhibits the bacterial activity which is instrumental in releasing nutrients from dead or decaying animal and vegetable matter; the ability of nitrifying bacteria to fix atmospheric nitrogen may also be restricted, leading to reduced soil fertility (Ontario: Ministry of the Environment 1980).

This reduction in bacterial activity, and the associated disruption of nutrient supply, may be sufficient to offset the benefits that some soils receive from acid rain in the form of extra nitrogen compounds (LaBastille 1981).

Changes in soil chemistry, initiated by acid rain, also lead to nutrient depletion. In a normally fertile soil, nutrients—such as calcium, potassium and magnesium—are present in the form of positively charged microscopic particles (cations) bonded by way of their electrical charge to clay and humus particles or other soil colloids. They can be removed from there by plants, as required, and are normally replaced by additional cations released into the soil by mineral weathering (Steila 1976). As acidic solutions pass through the soil, hydrogen ions replace the basic nutrient cations, which are then leached out of the soil in solution with sulphate and nitrate anions (Fernandez 1985). Regular acid-induced leaching of this type, leads to reduced soil fertility, and consequently affects plant growth. Needle yellowing in coniferous trees, for example, has been attributed to the removal of magnesium from acidified forest soils (Ulrich 1989).

The mobilization of toxic metals, such as aluminium, cadmium, zinc, mercury, lead, copper and iron, is another feature which accompanies soil acidification (Fernandez 1985). Most of these metals are derived from bedrock or soil minerals by natural weathering, but there is evidence from some areas, such as the northeastern United States, that atmospheric loading is also important (Johnson and Siccama 1983). Acid rain liberates the metals in ionic form, and they are carried in solution into groundwater, lakes and streams, or absorbed by plants (Park 1987). The detrimental effects of these toxic metals, such as aluminium, on the aquatic environment, are well-documented. Their impact on the terrestrial environment is less clear, however. Some metals, such as iron, are essential for growth, and only become toxic at higher concentrations; other metals may be present in amounts normally considered toxic, yet the vegetation is undamaged, presumably because it has adapted to the higher concentrations (Park 1987). The main claims that metals have initiated vegetation damage have come from western Germany, where high levels of aluminium in soils have been blamed, in part, for the forest decline in that area (Fernandez 1985). The aluminium restricts the development of the fine root systems of the trees to the upper part of the soil profile. If the topsoil dries out, the surviving deep roots are unable to supply enough water to meet the needs of the trees. Water stress occurs and growth rates decline (Ulrich 1989). Elsewhere, there is no clear evidence that tree growth has been impaired by toxic metal mobilization.

The damage attributed to acid rain is both visible and invisible. In some cases, the impact is only apparent after detailed observation and measurement. For example, a survey of annual rings in a mixed spruce, fir and birch forest exposed to acid rain in Vermont, revealed a progressive reduction in growth rates between 1965 and 1979 (Johnson and Siccama 1983). Between 1965 and 1983, in the same general area, there was also a 25 per cent decline in the above-ground biomass of natural sugar maple forest (Norton 1985). Physical damage to the fine root systems is another element common to trees in areas subject to acid rain (Tomlinson 1985).

Most of these symptoms can only be recognized following careful and systematic survey, but there are other effects which are more directly obvious, and which have received most public attention. They can be grouped together under the general term ‘tree dieback’, which describes the gradual wasting of the tree, inwards from the outermost tips of its branches.

Dieback has been likened to the premature arrival of autumn (Norton 1985). On deciduous trees, the leaves on the outermost branches begin to turn yellow or red in mid-summer; they dry out and eventually fall, well ahead of schedule. These branches will fail to leaf-out in the spring. In succeeding years, the problem will spread from the crown until the entire tree is devoid of foliage, and takes on a skeletal appearance, even in summer (Norton 1985). Coniferous trees react in much the same way. Needles turn yellow, dry up and fall off the branches; new buds fail to open or, if they do, produce stunted and distorted growth (Park 1987). The trees gradually weaken during these changes and become more and more vulnerable to insect attack, disease and the ravages of weather, all of which contribute to their demise (Norton 1985).

The maple groves of Ontario, Quebec and Vermont have been suffering progressive dieback since 1980 (Norton 1985), and it is now estimated that, in Quebec alone, more than 80 per cent of the maple stands show signs of damage (Robitaille 1986). Mortality rates for maples growing in Quebec have increased from 2 per cent per year to 16 per cent (presenting a potential $6 million loss for the province's maple sugar producers), and regeneration is well below normal (Norton 1985). There is as yet no conclusive proof that acid rain is the cause of dieback, nor that current acid rain levels are sufficient to prevent or diminish the germination and growth of maple seeds (Pitelka and Raynal 1989). Maple seedlings are sensitive to the presence of aluminium in the soil, but in most of the affected area aluminium levels are not high enough to be toxic (Thornton *et al.* 1986). Alternative explanations for the dieback, such as poor sugar bush management or disease—with or without a contribution from acid rain—have been put forward. However, the problem is common to both natural and managed groves, while disease usually follows rather than precedes the onset of dieback (Norton 1985). Dieback is now becoming prevalent in beech and white ash stands, but it is the damage to the maple which is causing greatest concern, particularly in Quebec, currently the source of 75 per cent of the world's supply of maple sugar (Norton 1985).

Deciduous trees are not the only victims of dieback. The coniferous forest of eastern North America has also suffered considerable decline (Johnson and Siccama 1983). The red spruce forests in the Adirondack, Green and White Mountains were particularly badly hit between the early 1960s and mid-1980s (Johnson *et al.* 1989). Since the greatest dieback occurred at higher elevations, where the trees are often enveloped in cloud for days at a time, it was hypothesized that persistent exposure to the high levels of acid common in these clouds was the main cause of the damage. Subsequent studies, however, provided no proof of a direct link between acidity and dieback in that setting (Johnson *et al.* 1989). There is evidence that winterkill played an important part in initiating the spruce decline (Johnson *et al.* 1989), and it has been suggested that exposure to acid stress caused the trees to be less capable of withstanding the extreme cold of winter (Haines and Carlson 1989).

Dieback is extensive in Europe also. By the mid-1980s, the symptoms had been recognized across fifteen countries in forests covering some 70,000 sq km (Park 1991). Damage was particularly extensive in what was then West Germany, where Ulrich and his colleagues first linked it to acid rain (Ulrich *et al.* 1980). It was estimated that one third of the trees in that country had suffered some degree of dieback; 75 per cent of the fir trees and 41 per cent of the spruce trees in the state of Baden-Wurttemberg, which includes the Black Forest, were damaged (Anon. 1983); 1,500 hectares of forest died in Bavaria in the late 1970s and early 1980s (Pearce 1982d). For a nation which prides itself in good forest management, such figures were horrendous. The death of the forests, or *Waldsterben* as it has became known, was progressing at an alarming, and apparently quickening, pace in the mid-1980s (Park 1987). Some recovery took place in the German forests after 1985 (Blank *et al.* 1988), but by the end of the decade perhaps as many as half the trees in the country were showing signs of damage (Park 1991). Other nations in Europe are affected, from Sweden with 38 per cent of its trees damaged, to Greece with 64 per cent. As more information becomes available for eastern Europe, it is clear that forest decline is also a serious problem in the Czech and Slovak republics, eastern Germany and Poland. In contrast, Norway does not fit the pattern, despite the exposure of its forests to acid rain. Decline is not widespread, and is present even in areas where acid precipitation is minimal (Abrahamsen *et al.* 1989).

Damage to existing trees is only part of the problem. The future of the forests is at stake also. Natural regeneration is no longer taking place in much of Central Europe, and even the planting of nursery-raised stock provides no guarantee of success (Tomlinson 1985). Developments such as these raise the spectre of the wholesale and irreversible loss of forest land. Such is the importance of the forest industry to many of the regions involved, that this would lead to massive economic disruption, and it is therefore not surprising that calls for action on acid rain from these areas became increasingly more strident—perhaps even desperate—through the 1980s (Pearce 1982b; Piette 1986). Although acid gas emissions have declined in Europe and North America in the last decade, allowing some limited recovery in a number of aquatic ecosystems (Last 1989), there is little evidence of similar improvements in terrestrial ecosystems. This may reflect the longer response time associated with the greater ecological complexity of the latter, but it may also support the claims of many scientists that there are no well-established physical links between acid rain and forest decline (Haines and Carlson 1989; Pitelka and Raynal 1989). The decline of European forests, for example, is now seen as a multifaceted problem in which acid precipitation may only be a minor contributor along with tree harvesting practices, drought and fungal attacks (Blank *et al.* 1988). In contrast, Ulrich—who first formulated the processes by which acid rain was thought to cause forest damage (see, for example, Ulrich 1983)—accepts the contributions of other factors, but continues to claim that they only come into play fully once soil acidification has made the forest vulnerable (Hauhs and Ulrich 1989). Until these differences are resolved, and the role of acid rain is better understood there is no guarantee that the greater control of acid emissions will have the desired effect of saving the forests.

## ACID RAIN AND THE BUILT ENVIRONMENT

Present concern over acid rain is concentrated mainly on its effect on the natural environment, but acid rain also contributes to deterioration in the built environment. Naturally acid rain has always been involved in the weathering of rocks at the earth's surface. It destroys the integrity of the rock by breaking down the mineral constituents and carrying some of them off in solution. All rocks are affected to some extent, but chalk, limestone and marble are particularly susceptible to this type of chemical weathering. Inevitably, when these rocks are used as building stone, the weathering will continue. In recent years, however, it has accelerated, in line with the increasing acidity of the atmosphere.

Limestone is a common building stone, because of its abundance, natural beauty and ease of working. Its main constituents are calcium and magnesium carbonates, which react with the sulphuric acid in acid rain to form the appropriate sulphate. These sulphates are soluble, and are washed out of the stone, gradually destroying the fabric of the building in the process. Further damage occurs when the solutions evaporate. Crystals of calcium and magnesium sulphate begin to form on or beneath the surface of the stone. As they grow, they create sufficient pressure to cause cracking, flaking and crumbling of the surface, which exposes fresh material to attack by acid rain (Anon. 1984). Limestone and marble suffer most from such processes. Sandstone and granite may become discoloured, but are generally quite resistant to acidity, as is brick. Acid damage to the lime-rich mortar binding the bricks may weaken brick-built structures, however (Park 1987). Structural steel and other metals used in modern buildings may also deteriorate under attack from acid rain (Ontario: Ministry of the Environment 1980).

By attacking the fabric of buildings, acid rain causes physical and economic damage, but it does more than that; it also threatens the world's cultural heritage. Buildings which have survived thousands of years of political and economic change, or the predation of warfare and civil strife, are now crumbling under the attack of acid rain. The treasures of ancient Greece and Rome have probably suffered more damage in the last 50 years than they did in the previous 2,000–3,000 years (Park 1987). On the great cathedrals of Europe—such as those in Cologne, Canterbury and Chartres—the craftsmanship of medieval stone masons and carvers may now be damaged beyond repair (Pearce 1982a; Park 1987). Few buildings in the industrialized regions of the world are immune, and damage to the Taj Mahal in India from sulphur pollution may be only the first indication that the problem is spreading to the developing world also (Park 1987). The faceless statues and crumbling cornices of the world's famous buildings receive most publicity, but less spectacular structures may provide important information on the rate at which damage is occurring and its relationship to acid emissions. In the United States, for example, researchers investigating the effects of acid rain on building materials have used the standardized marble gravestones in national military cemeteries, as controls in their field studies (Anon. 1984).

The chemical processes involved in acid rain attacks on the built environment are essentially the same as those involved in the natural environment, but there are some differences in the nature and provenance of the acidity. Damage in urban areas is more often associated with dry deposition than with wet, for example (Park 1987). Acidic particles falling out of the atmosphere close to their source land on buildings, and, once moisture is added, corrosion begins. Damage is usually attributed to deposition from local sources, such as the smelters or power stations commonly found in urban areas, with little of the long range transportation associated with acidification in the natural environment. However, in cities with little industrial activity, such as Ottawa, Canada, most of the damage will be caused by wet deposition originating some distance upwind (LaBastille 1981), and the same probably applies to acid corrosion of isolated rural structures (Park 1987). Since the various Clean Air Acts introduced in Europe and North America in the 1960s and 1970s had their greatest impact on urban pollution levels, it might be expected that the effects of acid rain on the built environment would be decreasing. There is some indication that this is so, but there appears to be a time lag involved, and it may be some time before the reduction in emissions is reflected in a reduction of acid damage to buildings and other structures (Park 1987).

## ACID RAIN AND HUMAN HEALTH

The infamous London Smog of 1952 developed as a result of meteorological conditions which allowed the build-up of pollutants within the urban atmosphere. Smoke, produced by domestic fires, power stations and coal-burning industries, was the most obvious pollutant, but the most dangerous was sulphuric acid, floating free in aerosol form or attached to the smoke particles (Williamson 1973). Drawn deep into the lungs, the sulphuric acid caused or aggravated breathing problems, and many of the 4,000 deaths attributed to the smog were brought about by the effect of sulphuric acid on the human respiratory system (Bach 1972). Although the Clean Air Acts of the 1960s and 1970s, along with such developments as the tall stacks policy, reduced the amount of sulphur compounds in urban air, recent studies in Ontario and Pennsylvania have indicated that elevated atmospheric acidity continues to cause chronic respiratory problems in these areas (Lippmann 1986).

The acid rain which causes respiratory problems is in a dry gaseous or aerosol form, and mainly of local origin. It is therefore quite different from the far-travelled wet deposition that has caused major problems in the natural environment. There is, as yet, no evidence that wet deposition is directly damaging to human health, but, because of its ability to mobilize metals, it may have important indirect effects (Park 1987). For example, in Norway the intake of aluminium in acidified water has been linked to chronic renal failure (Abrahamsen et al. 1989). Heavy metals such as copper, cadmium, zinc and mercury, liberated from soil and bedrock by acid rain, may eventually reach the human body via plants and animals in the food chain or through drinking water supplies. The corrosion of storage tanks and distribution pipes by acidified water can also add metals to drinking water: the liberation of lead from lead piping or from solder on copper piping is a particular concern. Although quality control in water treatment plants can deal with such problems (Ontario: Ministry of the Environment 1980), many areas subject to acid rain depend upon wells, springs and lakes, which provide an untreated water supply. This may expose users to elevated levels of such metals as lead and copper and although individual doses in all of these situations would be small, regular consumption might allow the metals to accumulate to toxic levels.

## SOLUTIONS TO THE PROBLEM OF ACID RAIN

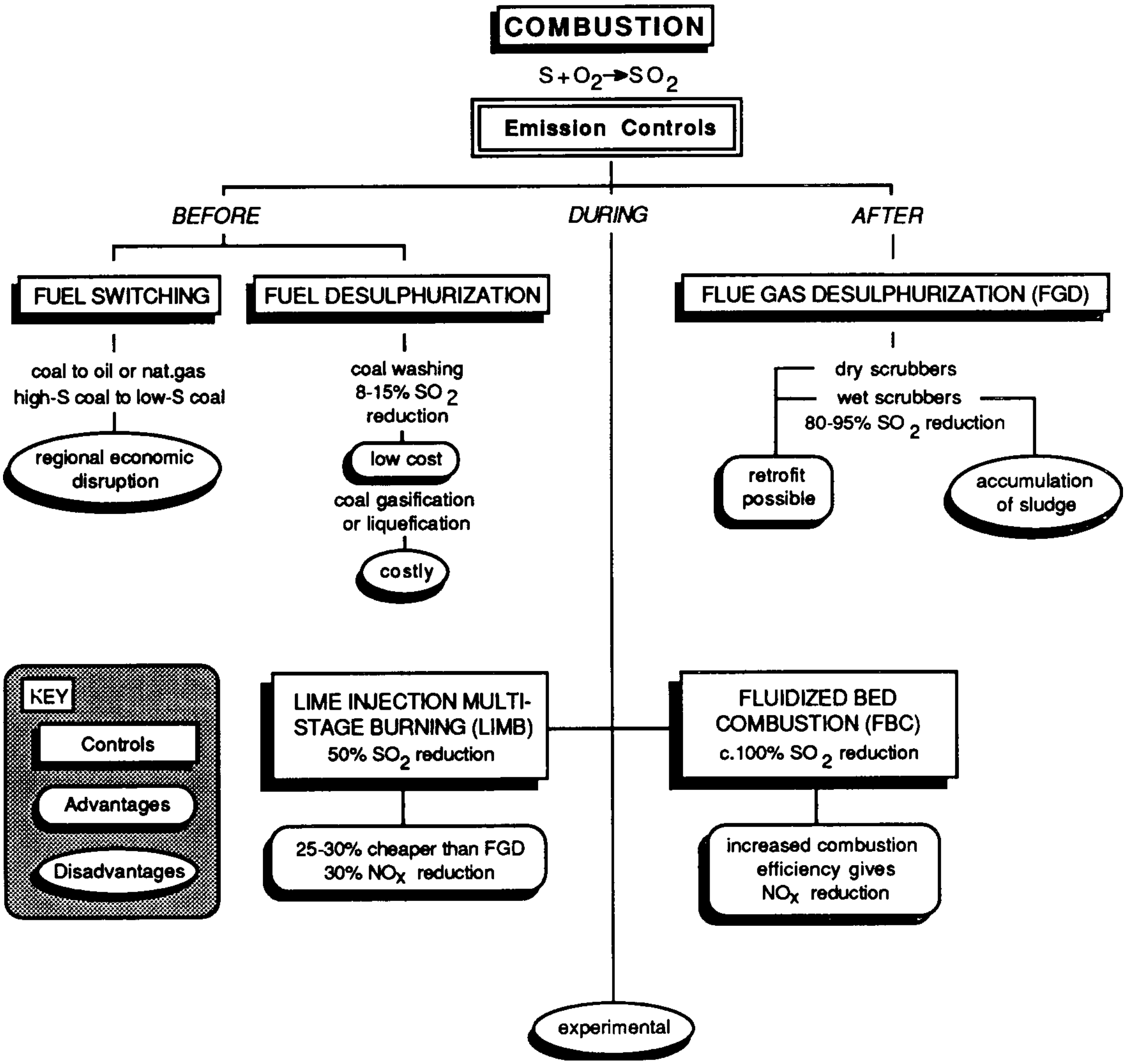
Although the cause and effect relationship between emissions of $SO_2$ and $NO_X$ and acid rain damage is not universally accepted, most of the solutions proposed for the problem involve the disruption of that relationship. The basic approach is deceptively simple. In theory, a reduction in the emission rate of acid forming gases is all that is required to slow down and eventually stop the damage being caused by the acidification of the environment. Translating that concept into reality has proved difficult, however.

The reduction in emissions of $SO_2$ and $NO_X$ is a long-term solution, based on prevention. It is also a solution in which the environment itself has a major role. As emissions decline, it must adjust until some new level of equilibrium, reflecting the decreased acidity, is attained. There is concern that in some areas the damage has gone too far to be reversed completely, and there is currently some support for this point of view. For example, $SO_2$ emissions in Britain have declined by nearly 40 per cent since 1970 (Caulfield and Pearce 1984), and, in Canada, emissions decreased by 45 per cent between 1970 and 1985 (Environment Canada 1991), yet the reduction in aquatic or terrestrial acidity downwind from these areas remains less than expected. The discrepancy may be explained in part by the continuing rise in $NO_X$ emissions, offsetting the decline in $SO_2$, but it is also possible that the link between reduced acidity and ecological recovery is not linear. In that case, a specific reduction in acid emissions might not bring about an equivalent reduction in environmental damage (Park 1991). In Lake Oxsjon in Sweden, for example, the pH fell from 6.8 to 4.5 between 1968 and 1977. Despite the marked reduction in $SO_2$ emissions from Britain and Sweden in the decade or so since then, the pH has only recovered to 4.9 (Mason 1990). Reductions of a similar magnitude have been identified in some Scottish lochs (Last 1989). Surveys in lakes in Ontario indicate that pH values may rise by small but significant amounts soon after acid input is reduced, but it may be 10 to 15 years before aquatic biota respond to the reduced acidity (Havas 1990). This indicates that natural recovery does seem to be possible, but that it is a slow process, taking much longer than the original acidification. It may also indicate that some direct human input will be necessary, either to initiate the recovery process or to speed it up.

One possible input is the addition of lime, which would produce an immediate reduction in acidity, and allow the recovery mechanisms to work more effectively. Lime has been used as a means of sweetening acid soils for many years, and may be the reason that in areas of acid soils agricultural land is less affected by acid rain than the natural environment. In areas where natural regeneration is no longer possible, the restoration of the original chemical balance of the soil by liming and appropriate fertilizer application might allow reforestation to be successful.

The same situation might apply in the aquatic environment. Simply re-stocking an acidified

*Figure 4.12* Reduction of sulphur dioxide through emission controls




*Source:* Various; see text

lake with fish cannot be successful unless some buffering agent is added. In 1973, several lakes in the Sudbury area were treated with calcium carbonate and calcium hydroxide in an attempt to reduce acid levels (Scheider *et al.* 1975). Acidity returned to normal and there was an increase in nutrient levels, but, in the lakes closest to Sudbury, copper and nickel remained at concentrations toxic to fish (Ontario: Ministry of the Environment 1980). Similar experiments in Sweden since the mid-1970s have involved the liming of some 3,000 lakes and 100 streams, and have provided encouraging results (Porcella *et al.* 1990). Reduced acidity is often followed by recovery among the aquatic biota, Lower organisms—such as phytoplankton—which reproduce rapidly recover first, followed eventually by amphibians and fish (Havas 1990). Artificial buffering of lakes in this way is only a temporary measure which may be likened to the use of antacid to reduce acid indigestion. The neutralizing effects of the lime may last longer than those of the antacid, but they do wear off in 3 to 5 years and re-liming is necessary as long as acid loading continues (Ontario: Ministry of the Environment 1980). The treatment of the environment with lime to combat acidity is only a temporary measure, at best. It can be used to initiate recovery, or to control the problem until abatement procedures take effect, but since it deals only with the consequences of acid rain rather than the causes, it can never provide a solution.

Most of the current proposals for dealing with acid rain tackle the problem at its source. They attempt to prevent, or at least reduce, emissions of acid gases into the atmosphere. The only way to stop acid emissions completely is to stop the smelting of metallic ores and the burning of fossil fuels. Modern society could not function without metals, but advocates of alternative energy sources—such as the sun, wind, falling water and the sea—have long supported a reduction in the use of fossil fuels. These alternative sources can be important locally, but it is unlikely that they will ever have the capacity to replace conventional systems. Nuclear power has also been touted as a replacement, since it can be used to produce electricity without adding gases to the atmosphere. It has problems of its own, however. Difficulties associated with the disposal of radioactive wastes remain to be resolved, and events such as the Chernobyl disaster of 1986 do little to inspire public confidence in nuclear power. Thus, although the replacement of fossilfuel-based energy systems with non-polluting alternatives has the potential to reduce acid rain, it is unlikely to have much effect in the near future.

Since $SO_2$ makes the greatest contribution to acid rain in North America and Europe, it has received most attention in the development of abatement procedures, whereas emissions of $NO_X$—which are both lower in volume and more difficult to deal with—have been largely neglected. Similarly the development of control technology has tended to concentrate on systems suitable for conventional power stations, since they are the main sources of acid gases (Kyte 1986a). Sulphur dioxide is formed when coal and oil are burned to release energy, and the technology to control it may be applied before, during or after combustion. The exact timing will depend upon such factors as the amount of acid reduction required, the type and age of the system and the cost-effectiveness of the particular process (see Figure 4.12).

One of the simplest approaches to the problem is fuel switching, which involves the replacement of high sulphur fuels with low sulphur alternatives. This may mean the use of oil or natural gas rather than coal. In Britain, for example, the recently privatized power industry is actively exploring the increased use of North Sea gas as a means of reducing $SO_2$ output, despite concern that this approach is a waste of a high premium fuel with a relatively short lifespan (Stevenson 1993). However, since most power stations use coal and are not easily converted to handle other fuels, fuel switching usually involves the replacement of one type of coal with another or even the blending of low and high sulphur coal. Much depends on the availability of the low sulphur product. In Britain, for example, the supply is limited (Park 1987), but in western Canada and the western United States, abundant supplies of low sulphur coal are available with a sulphur content only one-fifth of that which is normal in eastern coal (Cortese 1986). Such a difference suggests that fuel switching has a considerable potential for reducing $SO_2$ production, yet wholesale substitution is uncommon. The problem is a geographical one. The main reserves of low-sulphur coal are in the west, far removed from the large consumers in the east. Transport costs are therefore high, and complete switching becomes economically less attractive than other methods of reducing $SO_2$ output. Compromise is possible. Rather than switching entirely, Ontario Hydro, the major public electricity producer in the province, has a well-established practice of blending low-sulphur, western Canadian coal, with the high-sulphur product from the eastern United States. As a result of this plus the use of washed coal, the utility's $SO_2$ output per unit of electricity has been declining with some regularity since the early 1970s (Ontario: Ministry of the Environment 1980).

The amount of $SO_2$ released during combustion can be reduced if the coal or oil is treated beforehand to remove some of the included sulphur, in a process called fuel desulphurization. The methods can be quite simple and quite cost effective. Crushing and washing the coal, for example, can reduce subsequent $SO_2$ emissions by 8 to 15 per cent (Park 1987), which represents a reduction of 1.5 to 2 million tonnes of $SO_2$ per year in the eastern United States alone (Cortese 1986). More complex chemical cleaning methods involving the gasification or liquefaction of the coal are also possible, but at considerable cost (Ramage 1983).

If it is not possible to reduce sulphur levels significantly prior to combustion, there are techniques which allow reduction during the combustion process itself. Basically, they involve the burning of coal in the presence of lime. Although the technology has been studied since the 1950s, it has yet to be adopted on a large scale (Ramage 1983). There are two promising developments, however, which are expected to be available in the early 1990s. These are, lime injection multi-stage burning (LIMB) and fluidized bed combustion (FBC). LIMB involves the injection of fine lime into the combustion chamber, where it fixes the sulphur released from the burning coal to produce a sulphate-rich lime ash. This process can reduce $SO_2$ emissions by 35–50 per cent (Burdett *et al.* 1985). In the FBC system, air under pressure is injected into a mixture of coal, limestone, and sand, until the whole mass begins to act like a boiling fluid (Ramage 1983). The continual mixing of the materials under such conditions ensures that combustion is very efficient, and that up to 90 per cent of the sulphur in the fuel is removed (Kyte 1986b). It has the added advantage that, since furnace temperatures are relatively low, it reduces $NO_X$ emissions also. In the United States, four thermal electric generating stations utilizing FBC technology came on stream in the late 1980s. Together they produce only 400 MW, but it has been estimated that a further 150 stations—producing 20,000 MW—could be retrofitted (Ellis *et al.* 1990).

Flue gas desulphurization (FGD) is the name given to a group of processes which remove $SO_2$ from the gases given off during combustion. The devices involved are called scrubbers, and may be either dry or wet operations. The simplest dry scrubbers act much like filters, removing the gas on contact by chemical or physical means. Sulphur dioxide passing through a dry pulverized limestone filter, for example, will react chemically with the calcium carbonate to leave the sulphur behind in calcium sulphate (Williamson 1973). Other filters—such as activated charcoal—work by adsorbing the gas on to the filter (Turk and Turk 1988).

Wet scrubbers are more common than the dry variety. The flue gases may be bubbled through an alkaline liquid reagent, which neutralizes the $SO_2$ and produces calcium sulphate in the process (Kyte 1981). A variation on this approach involves the use of a lime slurry through which the flue gases are passed, and in more modern systems the combustion gases are bombarded by jets of lime (LaBastille 1981) or pass through spray systems (Ramage 1983). The system described by LaBastille removes 92 per cent of the $SO_2$ from the exhaust gases and many scrubbers achieve a reduction of between 80 and 95 per cent (Cortese 1986). By 1978, Japanese industry had installed scrubbers on more than 500 plants (Howard and Perley 1991). In the United States, some 70,000 MW of electricity is currently being produced from plants employing FGD technology, and in Canada, a FGD retrofit programme is in place with the goal of reducing $SO_2$ emissions by about 50 per cent by 1994 (Ellis *et al.* 1990). The European Community directive of 1988—requiring all EC nations to reduce $SO_2$

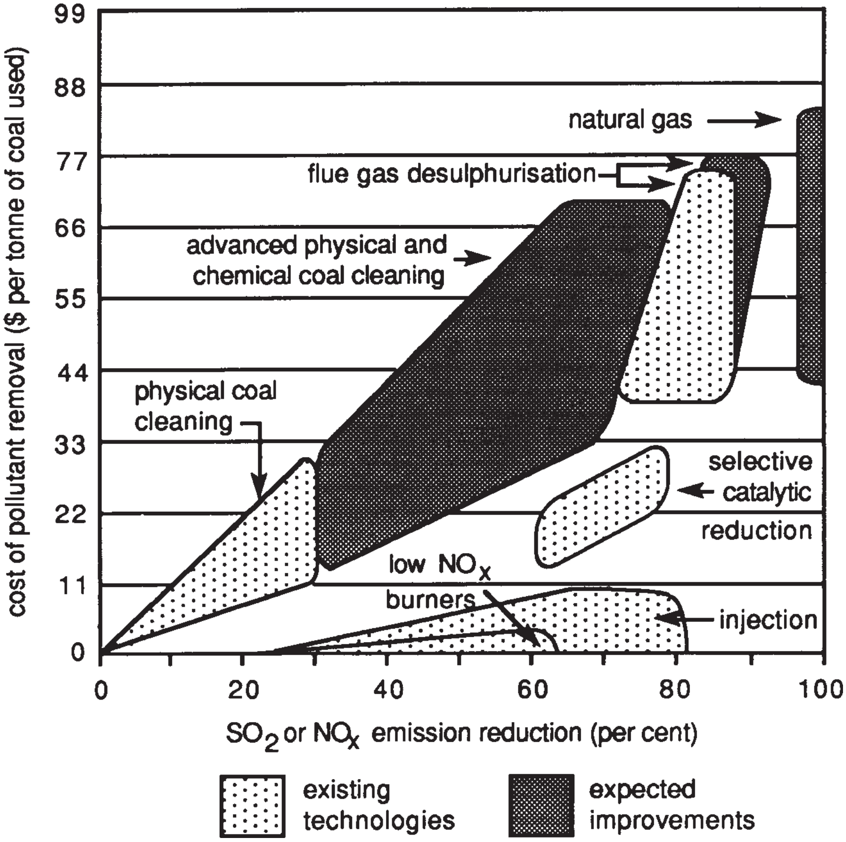
emissions by stages up to 70 per cent by 2003—will be met in large part by the installation of FGD equipment (Park 1991).

Flue gas desulphurization is thus one of the most common methods of $SO_2$ removal, in part because of the high efficiencies possible, but for other reasons also. Scrubbers are technically quite simple, and can be added to existing power plants relatively easily. Retrofitting existing plants in this way is less expensive than building entirely new ones, and in some systems the recovery of sulphuric acid for sale can help to offset the cost.

None of the FGD systems described works well to reduce emissions of $NO_X$ from power plants. The best results for $NO_X$ control—up to 80 per cent reduction—have been obtained using a selective catalytic reduction process (SCR), which breaks the $NO_X$ down into the original N and O, but the price is high. To retrofit an existing thermal power station would cost an estimated $10,000 for every 1,000 kg of $NO_X$ removed, and maintenance costs would be substantial because the life of the catalyst is short (Ellis *et al.* 1990). Difficulties also exist with emission reductions from automobile exhausts. The development of technology that can produce a cooler burning internal combustion engine, or perhaps replace it completely, may be required before emissions of $NO_X$ from that source are reduced significantly (Park 1987).

It is now technically possible to reduce $SO_2$ emissions to very low levels. However, as is common with many environmental problems, technology is only one of the elements involved. In many cases, economics and politics have retarded the implementation of technical solutions

*Figure 4.13* Technologies and trade-offs in power station emission control




*Source:* From Ridley (1993)

to environmental problems, and that is certainly the case with acid rain.

## THE ECONOMICS AND POLITICS OF ACID RAIN

Government participation in pollution abatement is not a new phenomenon, but, in recent years, particularly following the Clean Air legislation of the 1960s and 1970s, the role of government has intensified, and pollution problems have become increasingly a focus for political intervention. Thus, when acid rain emerged as a major environmental problem, it was inevitable that any solution would involve considerable governmental and political activity. Given the magnitude of the problem it also became clear that it could be solved only at considerable cost, and economic and political factors are now inexorably linked in any consideration of acid rain reduction. Additional complexity is provided by the international nature of the problem.

The costs of acid rain reduction will vary depending upon such factors as the type of abatement equipment required, the reduction of emission levels considered desirable, and the amount of direct rehabilitation of the environment considered necessary (see Figure 4.13). For example, one report prepared by the Office of Technology Assessment of the US Congress (Anon. 1984) estimated that a 35 per cent reduction in $SO_2$ levels in the eastern United States by 1995, would cost between $3 and $6 billion. In a series of five bills presented to the U.S. Congress in 1986 and 1987 costs ranged from $2.5 to $22.6 billion (Ellis *et al.* 1990). A 50 per cent reduction in Canada has been estimated to cost $300 million (Israelson 1987). In Britain, a 60 per cent reduction of $SO_2$ from the 1980 levels had an estimated price-tag of between £1–2 billion (c. $2–4 billion) (Park 1991; Ridley 1993) while a 90 per cent reduction was priced at £5 billion (c. $10 billion) (Pearce 1992e). Such costs are not insignificant, and in all likelihood would be imposed, directly or indirectly, on the consumer.

*Table 4.1* Commitment of selected nations to the reduction of sulphur dioxide emissions

| | *Promised $SO_2$ reduction from 1980 level* |
|---|---|
| Austria | 50% by 1995 |
| Bulgaria | 30% by 1995 |
| Canada | 50% by 1994 |
| Denmark | 50% by 1995 |
| Finland | 50% by 1995 |
| France | 50% by 1990 |
| West Germany (1983) | 60% by 1993 |
| East Germany (1984) | 30% by 1993 |
| Netherlands | 40% by 1995 |
| Norway | 50% by 1994 |
| Sweden | 65% by 1995 |
| Switzerland | 30% by 1995 |
| USSR (1984) | 30% by 1993 |
| United Kingdom | 60% by 2003 |
| USA | 35% by 2000 |
| EC | 70% by 2003 |

*Source:* Various sources including Park (1991)

Increased costs of this type have to be set against the costs of continuing environmental damage if no abatement is attempted, but the latter often involve less tangible elements, which are difficult to evaluate. The death of a lake from increased acidity, for example, may involve a measurable economic loss through the decline of the sports or commercial fishery (Forster 1985), but there are other items, such as the aesthetic value of the lake, which cannot always be assessed in real monetary terms. Thus, the traditional cost/benefit analysis approach is not always feasible when dealing with the environmental impact and abatement of acid rain.

The first major international initiative to deal with acid rain took place in 1979, when the UN Economic Commission for Europe (UNECE) drafted a Convention on the Long Range Transportation of Air Pollutants. The Convention was aimed at encouraging a coordinated effort to reduce $SO_2$ emissions in Europe, but the thirty-five signatories also included Canada and the United States (Park

1987). Although not a legally binding document, it did impose a certain moral obligation on the signatories to reduce acid pollution. That was generally insufficient, however, and after additional conferences in Stockholm (1982), Ottawa (1984) and Munich (1984), the UNECE was forced, in 1985, to prepare an additional protocol on sulphur emissions. This was a legally binding document, which required its signatories to reduce transboundary emissions of $SO_2$ by 30 per cent (of the 1980 levels) before 1993. Many subsequently improved on that figure (see Table 4.1), but fourteen of the original thirty-five participants in the 1979 ECELRTAP Convention refused to sign, among them Britain and the United States (Park 1987). Subsequently, both have become embroiled with neighbouring states, which signed the protocol, and the resulting confrontation provides excellent examples of the economic and political problems accompanying attempts to reduce acid rain at the international level.

### Canada and the United States

Both Canada and the United States are major producers of acid gases (see Figure 4.14). Canada ranks fifth overall, in the global $SO_2$ emissions table (Park 1987), but produces less than one fifth of the US total. Canadian emissions of $NO_X$ are only one tenth of those in the US. When *per capita* emissions are considered, however, the Canadian output of $SO_2$ is about double that of the US and $NO_X$ *per capita* output is about the same north and south of the border (Ellis *et al.* 1990). Both countries are also exporters of acid gases, with the United States sending three times as much $SO_2$ to Canada as Canada sends to the United States (Cortese 1986). It is this discrepancy, and the damage that it causes, which is at the root of the North American acid rain controversy.

As a member of the so-called '30 per cent club', Canada is obligated to reduce $SO_2$ emissions by 30 per cent of the 1980 base level before 1993, and has already implemented abatement programmes which will make a 50 per cent reduction possible by 1994 (Israelson 1987). Over 80 per cent of the 1994 objective had been met by 1991 (Environment Canada 1991). Such commitments as have been made by the United States, have been in the form of finance for increased research. Sulphur dioxide emissions have been reduced in New England and in the Mid-Atlantic states, but emissions continue to increase in the mid-west and southeastern states (Cortese 1986). It is possible that by the year 2000 $SO_2$ emissions will have risen by 8 to 13 per cent (Ellis *et al.* 1990), although legislation has been put in place to reduce emissions by some 9 million tonnes (Howard and Perley 1991).

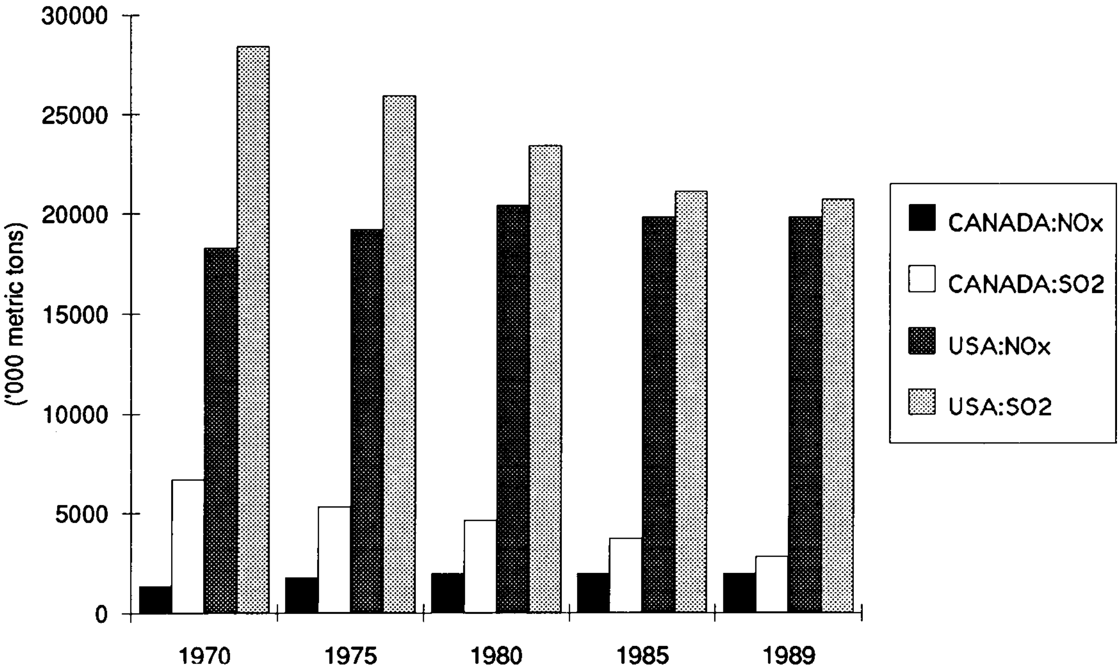
The pollution most affecting Canada comes from the mid-west, particularly the Ohio valley, where six states emit more than a million tonnes of $SO_2$ per year (Israelson 1987). This area, too, is the most resistant to abatement procedures because of their potentially negative impact on a regional economy based on high-sulphur bituminous coal, and its representatives have lobbied strongly and successfully against the institution of emission controls.

Such opposition to acid rain control soured relationships between Canada and the United States. Discussions between the two countries went on for over a decade before any substantive agreement on the problem of transboundary transportation of acid rain was reached. This came about finally as part of a comprehensive US Clean Air Act passed into law in 1990 (Howard and Perley 1991). The full effects will not be felt until the end of the century, but the legislation ensures a brighter future for the acid sensitive environment of eastern Canada and the United States.

### Britain and Scandinavia

Britain was one of the few nations in Europe not to join the '30 per cent club' when it was formed, although it subsequently revealed plans to reduce $SO_2$ emissions by 60 per cent. Situated to the north-west of the continent, it was relatively free from external emissions of

*Figure 4.14* Emissions of $SO_2$ and $NO_2$ in Canada and the United States: 1970–89

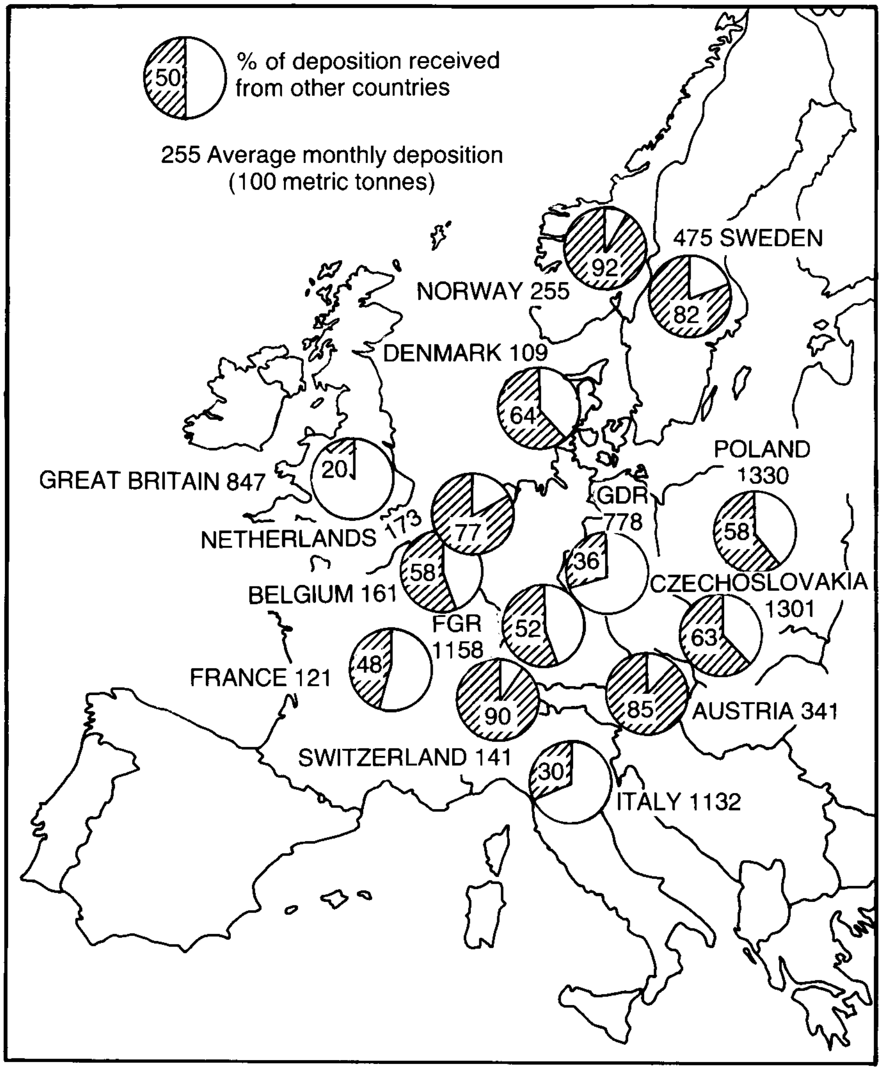



*Source:* Based on data in World Resources Institute (1992)

acid pollution, but added more than 4.5 million tonnes annually to the westerly air stream (Park 1987). In the early 1980s an estimated 25 per cent of the $SO_2$ leaving Britain was deposited in the North Sea, 4 per cent landed in Norway and Sweden and 6 per cent continued on to fall in the USSR (Pearce 1982d). Between 1980 and 1985, $SO_2$ emissions from British industry fell by about 25 per cent, but levelled off or rose slightly after that (Mason 1990). At that time, Britain was the largest producer of acid pollution in Europe after the USSR; Norway and Sweden were among the lowest and made a limited contribution to their own acid rain problem (Park 1987) (see Figure 4.15). In the acid rain falling on Norway, for example, the contribution from British sources was twice that from local Norwegian sources (Pearce 1982d). A considerable proportion of the acid rain falling in Scandinavia originated in East Germany, but it was to Britain that the Scandinavians turned to seek help in reducing the environmental damage being caused by acid rain.

Much of the blame for the acid rain damage in Scandinavia came to rest on the shoulders of the Central Electricity Generating Board (CEGB), the body which controlled electric power production in England. Emissions from CEGB power stations were responsible for more than half the $SO_2$ produced in Britain (Pearce 1984). Thus, any planned reduction in emissions required the cooperation of the CEGB. The Board, in common with most authorities in Britain, argued that the problem required further study, but that position eventually became untenable. In 1986, for the first time, Britain

*Figure 4.15* The balance of trade in sulphur dioxide in 1980




*Source:* From Park (1987)

agreed with Norway that acid rain originating in Britain was causing problems in the Norwegian environment. Subsequently, the British government announced its intentions to cut $SO_2$ emissions by 14 per cent—commendable, perhaps, but still well below that required for entry into the '30 per cent club' (Park 1987).

An agreement reached by the Environment Ministers of the EC in June 1988 required a 70 per cent reduction in emissions by the year 2003. Britain agreed only to a 60 per cent reduction and the CEGB initiated a series of measures aimed at meeting that requirement (Kyte 1988). By the following year, planning was in place to fit FGD equipment to six coal-fired power stations at a total cost of some £2 billion (c. $4 billion), but the whole process was thrown into disarray by the privatization of the electricity generating industry in Britain, which saw the CEGB replaced by two private com-panics in 1990. After some consideration of fuel-switching as a cheaper alternative, both companies reverted to FGD technology for emission control, but only at three stations rather than the original six (Park 1991).

Although this procrastination means that the proposed emission reductions will take longer to achieve, it may allow Britain to take advantage of new technology currently under development. Experiments with systems such as LIMB which involve the furnace injection of acid reducing chemicals, promise emission reductions that are more cost-effective than those of existing scrubber technology (Ridley 1993). The installation of these new, cheaper systems may deal with some of the economic issues which have contributed to the slow adoption of emission control strategies in the past. Ironically, the environmental effects of reduced acid emissions may never be fully known. Cooperative studies by British and Scandinavian scientists have all but ended, and many of the research funds available for the study of acid rain in the 1970s and 1980s have been lost to apparently more pressing issues, including global warming and ozone depletion (Pearce 1990).

## SUMMARY

Acid rain is a natural product of atmospheric chemical reactions. Inadvertent human interference in the composition of the atmosphere, through the addition of $SO_2$ and $NO_X$, has caused it to develop into a major environmental problem. It is mainly confined to the industrialized areas of the northern hemisphere at present, but has the potential to become a problem of global proportions. Acid rain damage is extensive in the aquatic environment, and is increasingly recognized in the terrestrial environment. Damage to buildings is common in some areas, but the effect of acid rain on human health is less obvious.

Progress towards the large scale abatement of acid emissions has been slow, and methods for controlling $NO_X$ lag behind those for dealing with $SO_2$. Emissions of sulphur dioxide are beginning to decline in many areas. Although lakes and forests damaged by acid rain will take some time to recover, action is being taken to improve the situation, and that, in itself, is psychologically important. Finally, much has been written about the necessity to 'clean-up' acid rain. Ironically, the acidity is really the end-product of a series of natural cleansing processes by which the atmosphere attempts to maintain some degree of internal chemical balance.

## SUGGESTIONS FOR FURTHER READING

Adriano, D.C. and Haas, M. (1989) *Acidic Precipitation; vol. 1: Case Studies,* New York: Springer-Verlag.

Howard, R. and Perley, M. (1991) *Poisoned Skies,* Toronto: Stoddart.

Park, C.C. (1987) *Acid Rain: Rhetoric and Reality,* London: Methuen.

# 5

# Atmospheric turbidity

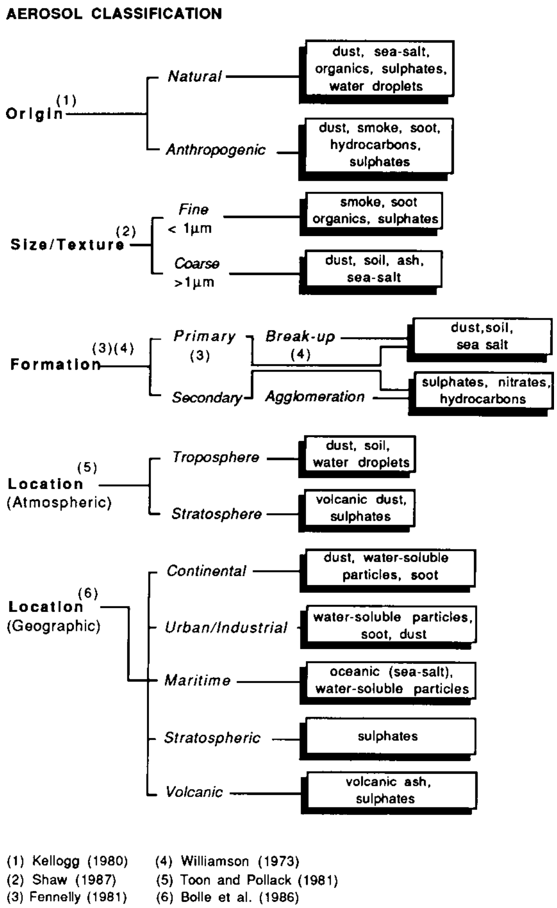
One of the more obvious indications of atmospheric pollution is the presence of solid or liquid particles, called aerosols, dispersed in the air. These aerosols are responsible for phenomena as diverse as the urban smogs that bedevil the world's major cities, and the spectacular sunsets which often follow major volcanic eruptions. The concentration and distribution of particulate matter in the atmosphere is closely linked to climatic conditions. Some local or regional climates encourage high aerosol concentrations, as in Los Angeles, for example, with its combination of high atmospheric pressure, light winds and abundant solar radiation. On a global scale, the mid-latitude westerlies and their associated weather systems, already implicated in the distribution of acid rain are responsible for the transportation of aerosols over long distances in the troposphere. The jet streams in the upper atmosphere are also involved in the distribution of aerosols, carrying particles around the world several times before releasing them. Knowledge of such relationships has important practical implications. At the local level, the success of pollution abatement programmes often depends upon an understanding of the impact of climate on aerosol distribution. At a continental, or even hemispheric scale, the relationship between atmospheric circulation patterns and the spread of particulate matter can be used to provide an early warning of potential problems following catastrophic events such as volcanic eruptions or nuclear accidents. In such situations, the atmospheric aerosols are responding to existing climatic conditions. There has been growing concern in recent years that they may do more than that; they may also be capable of initiating climatic change.

## AEROSOL TYPES, PRODUCTION AND DISTRIBUTION

The total global aerosol production is presently estimated to be between 2-3×$10^9$ tonnes per annum, and on any given day perhaps as many as 1×$10^7$ tonnes of solid particulate matter is suspended in the atmosphere (Bach 1979; Cunningham and Saigo 1992; Ahrens 1993). Under normal circumstances, almost all of the total weight of particulate matter is concentrated in the lower 2 km of the atmosphere in a latitudinal zone between 30°N and 60°N (Fennelly 1981). The mean residence time for aerosols in the lower troposphere is between 5 and 9 days, which is sufficiently short that the air can be cleansed in a few days once emissions have stopped (Williamson 1973). The equivalent time in the upper troposphere is about one month, and in the stratosphere the residence time increases to two to three years (Williamson 1973). As a result, anything added to the upper troposphere or stratosphere will remain in circulation for a longer time, and its potential environmental impact will increase.

Aerosols can be classified in a number of ways, but most classifications include such elements as origin, size and development, sometimes individually, sometimes in combination (see Figure 5.1). Most of the atmosphere's aerosol

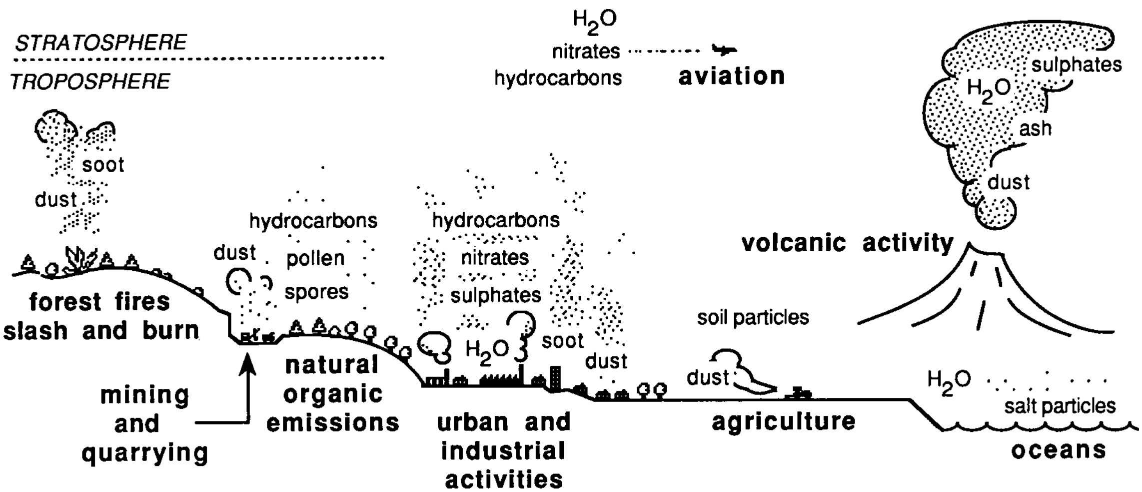
*Figure 5.1* A sample of the different approaches used in the classification of atmospheric aerosols




content—perhaps as much as 90 per cent (Bach 1979)—is natural in origin, although anthropogenic sources may be dominant locally, as they are in urban areas, for example (see Figure 5.2). Dust particles created during volcanic activity, or carried into the troposphere during dust storms, are examples of common natural aerosols. Dust blown eastwards from the Gobi Desert and adjacent arid lands of northern China is a significant constituent of the atmosphere in Beijing in April and May. Less frequent storms can also have local significance. A major dust storm in Australia in the summer of 1983 carried dust as high as 3.6 km into the atmosphere and deposited 106 kg of dust per hectare over the city of Melbourne (Lourensz and Abe 1983). That dust was picked up from the desiccated wheat fields and overgrazed pastures of Victoria and New South Wales, and farming practices, along with quarrying and a variety of industrial processes make an important contribution to dust of anthropogenic origin (Williamson 1973). Natural particles of organic origin—such as the terpenes considered responsible for the haze common over such areas as the Blue Mountains of Virginia—join hydrocarbon emissions from human activities to provide an important group of organic aerosols. Total organic emissions in the world have been estimated at as much as $4.4 \times 10^8$ tonnes per annum (Fennelly 1981).

Bolle *et al.* (1986) have grouped aerosols into several mixtures, which include combinations of the different particle types (see Figure 5.1). Three of these are geographically based. In the continental mixture, dust-like particles of natural origin predominate (70 per cent of the total), and most of these are confined to the troposphere. They may be carried over considerable distance, however; dust from the Sahara and Sahel regions of Africa has been carried on the tropical easterlies to the Caribbean (Morales 1986). Logically, volcanically produced aerosols could be included in the continental mixture, but, perhaps because of the major contribution of volcanic eruptions to aerosol loading, volcanic ash has been included as a separate item in the classification. In the urban/industrial mix, water soluble aerosols make up more than 60 per cent of the total. They are of anthropogenic origin, and include a high proportion of sulphates. Soot and water vapour are other important products of urban and industrial activities, but mechanically produced dust particles are of relatively minor importance. The effects of individual urban/industrial aerosols may be enhanced by combination with other constituents of the atmosphere. Chemical particles—soot and fine dust, for example—may act as condensation nuclei for the water vapour, and the net result is to increase cloudiness in urban/industrial areas.

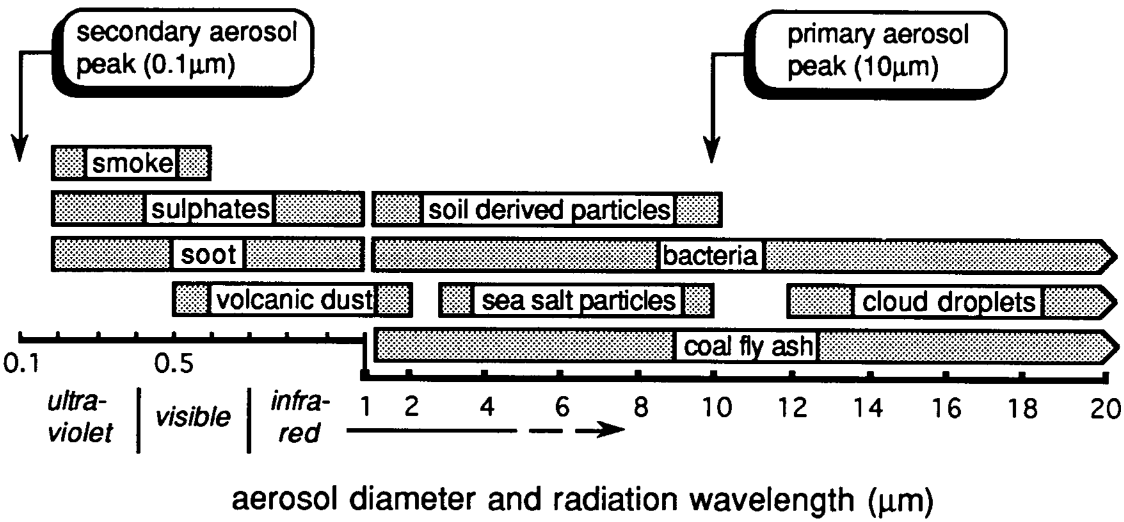
*Figure 5.2* Diagrammatic representation of the sources and types of atmospheric aerosols




Aerosols of urban and industrial origin are normally considered to be restricted in their distribution, since they are mainly released into the lower troposphere. However, products of urban combustion found in the Arctic and the increasing levels of sulphates in the stratosphere, suggest that their effects now extend beyond the local area (Shaw 1980). The third geographically based aerosol mixture recognized by Bolle *et al.* (1986) is maritime in origin. It includes water and sea-spray particles for the most part, with only a small proportion of water-soluble particles (c. 5 per cent).

Aerosols can range in size from a few molecules to a visible grain of dust, but the distribution across that range is not even. The

*Figure 5.3* A comparison of the size-range of common aerosols with radiation wavelength



main mass of particulates is concentrated in two peaks, one between 0.01 micrometre (μm) and 1 μm, centred at 0.1 μm and the other between 1 μm and 100 μm (see Figure 5.3), centred at 10 μm (Shaw 1987). The smaller particles in the first group are called secondary aerosols since they result from chemical and physical processes which take place in the atmosphere. They include aggregates of gaseous molecules, water droplets and chemical products such as sulphates, hydrocarbons and nitrates. As much as 64 per cent of total global aerosols are secondary particulates, 8 per cent of them anthropogenic in origin from combustion systems, vehicle emissions and industrial processes. The other 56 per cent are from natural sources such as volcanoes, the oceans and a wide range of organic processes (Fennelly 1981). Some estimates suggest that sulphate particles are now the largest group of atmospheric aerosols, accounting for as much as 50 per cent of all secondary particles (Toon and Pollack 1981). Most of the tropospheric sulphates are of anthropogenic origin, and contribute to the problems of acid rain (see Chapter 4) whereas those found in the stratosphere are most likely to be the products of volcanic eruptions. The larger particles with diameters between 1 and 100 μm are called primary aerosols, and include soil, dust and solid industrial emissions, usually formed by the physical breakup of material at the earth's surface (Fennelly 1981). There is some evidence that these groupings are a direct result of the processes by which the aerosols are formed. Mechanical processes are unable to break substances into pieces smaller than 1 μm in diameter, whereas the growth of secondary particles appears to cease as diameters approach 1 μm. (Shaw 1987).

## AEROSOLS AND RADIATION

Atmospheric aerosols comprise a very heterogeneous group of particles, and the mix within the group changes with time and place. Following volcanic activity, for example, the proportion of dust particles in the atmosphere may be particularly high; in urban areas, such as Los Angeles, photochemical action on vehicle emissions causes major increases in secondary particulate matter; over the oceans, 95 per cent of the aerosols may consist of coarse sea-salt particles. Such variability makes it difficult to establish the nature of the relationship between atmospheric aerosols and climate. It is clear, however, that the aerosols exert their influence on climate by disrupting the flow of radiation within the earth/atmosphere system, and there are certain elements which are central to the relationship. The overall concentration of particulate matter in the atmosphere controls the amount of radiation intercepted, while the optical properties associated with the size, shape and transparency of the aerosols determines whether the radiation is scattered, transmitted or absorbed (Toon and Pollack 1981). The attenuation of solar radiation caused by the presence of aerosols provides a measure of atmospheric turbidity, a property which, for most purposes, can be considered as an indication of the dustiness or dirtiness of the atmosphere.

Several things may happen when radiation strikes an aerosol in the atmosphere. If the particle is optically transparent, the radiant energy passes through unaltered, and no change takes place in the atmospheric energy balance. More commonly, the radiation is reflected, scattered or absorbed—in proportions which depend upon the size, colour and concentration of particles in the atmosphere, and upon the nature of the radiation itself (see Figure 5.3). Aerosols which scatter or reflect radiation increase the albedo of the atmosphere and reduce the amount of insolation arriving at the earth's surface. Absorbent aerosols will have the opposite effect. Each process, through its ability to change the path of the radiation through the atmosphere, has the potential to alter the earth's energy budget. The water droplets in clouds, for example, are very effective in reflecting solar energy back into space, before it can become involved in earth/atmosphere processes. Some of the energy scattered by aerosols will also be lost to the system, but a proportion will be scattered forward towards its original destination. Most aerosols, particularly sulphates and fine rock particles scatter solar radiation very effectively.

The most obvious effects of scattering are found in the visible light sector of the radiation spectrum. Particles in the 0.1 to 1.0 µm size range scatter light in the wavelengths at the blue end of the spectrum, while the red wavelengths continue through. As a result, when the aerosol content of the atmosphere is high, the sky becomes red (Fennelly 1981). This is common in polluted urban areas towards sunset when the path taken by the light through the atmosphere is lengthened, and interception by aerosols is increased. Natural aerosols released during volcanic eruptions produce similar results. The optical effects which followed the eruption of Krakatoa in 1883, for example, included not only magnificent red and yellow sunsets, but also a salmon pink afterglow, and a green colouration when the sun was about 10° above the horizon (Lamb 1970). As well as being aesthetically pleasing, the sequence and development of these colours allowed observers to calculate the size of particles responsible for such optical phenomena (Austin 1983).

Among the atmospheric aerosols, desert dust and soot particles readily absorb the shorter solar wave lengths (Toon and Pollack 1981; Lacis *et al.* 1992) with soot a particularly strong absorber across the entire solar spectrum (Turco *et al.* 1990). The degree to which a substance is capable of absorbing radiation is indicated by its specific absorption coefficient. For soot, this value is 8–10 $m^2g^{-1}$, which means that 1 g of soot can block out about two-thirds of the light falling on an area of 8–10 $m^2$ (Appleby and Harrison 1989). Individual soot particles in the atmosphere are approximately 0.1 µm in diameter and tend to link together in branching chains or loose aggregates. With time these clusters become more spherical and their absorption coefficient declines, but even when the aggregate diameters exceed 0.4 µm, the specific absorptivity may remain as high as 6 $m^2g^{-1}$ (Turco *et al.* 1990). Thus, the injection of large amounts of soot into the atmosphere has major implications for the earth's energy budget.

In addition to disrupting the flow of incoming solar radiation, the presence of aerosols also has an effect on terrestrial radiation. Being at a lower energy level, the earth's surface radiates energy at the infrared end of the spectrum. Aerosols—such as soot, soil and dust particles—released into the boundary layer absorb infrared energy quite readily, particularly if they are larger than 1.0 µm in diameter (Toon and Pollack 1981), and as a result will tend to raise the temperature of the troposphere. However, the absorption efficiency of specific particles varies with the wavelength of the radiation being intercepted. The absorption coefficient of soot at infrared wavelengths, for example, is only about one-tenth of its value at the shorter wavelengths of solar radiation. In addition, since they are almost as warm as the earth's surface, tropospheric aerosols are less efficient at blocking the escape of infrared radiation than colder particles, such as those in the stratosphere (Bolle *et al.* 1986). Thus, longer-wave terrestrial radiation can be absorbed by particles in the stratosphere, and re-radiated back towards the lower atmosphere where it has a warming effect. Much depends upon the size of the stratospheric aerosols. If they are smaller in diameter than the wavelengths of the outgoing terrestrial radiation, as is often the case, they tend to encourage scattering and allow less absorption (Lamb 1970). The net radiative effects of particulate matter in the atmosphere are difficult to measure or even estimate. They include a complexity which depends upon the size, shape and optical properties of the aerosols involved, and upon their distribution in the stratosphere and troposphere.

Any disruption of energy fluxes in the earth/atmosphere system will be reflected ultimately in changing values of such climatological parameters as cloudiness, temperature or hours of bright sunshine. Although atmospheric aerosols produce changes in the earth's energy budget, it is no easy task to assess their climatological significance. Many attempts at that type of assessment have concentrated on volcanic dust, which for a number of reasons is particularly suitable for such studies. For example, the source of the aerosols can be easily pin-pointed and the volume of material injected into the atmosphere can often be calculated; the dust includes particles from a broad size-range and it is found in both the troposphere and the stratosphere. Recent studies, however, have suggested that the sulphate particles produced during volcanic eruptions have a greater impact on the energy budget than volcanic dust and ash.

## VOLCANIC ERUPTIONS AND ATMOSPHERIC TURBIDITY

The large volumes of particulate matter thrown into the atmosphere during periods of volcanic activity are gradually carried away from their sources to be redistributed by the wind and pressure patterns of the atmospheric circulation. Dust ejected during the explosive eruption of Krakatoa, in 1883, encircled the earth in about two weeks following the original eruption (Austin 1983), and within 8 to 12 weeks had spread sufficiently to increase atmospheric turbidity between 35°N and 35°S (Lamb 1970). The diffusion of dust from the Mount Agung eruption in 1963 followed a similar pattern (Mossop 1964) and in both cases the debris eventually spread polewards until it formed a complete veil over the entire earth. The cloud of sulphate particles ejected from El Chichón in 1982 was carried around the earth by the tropical easterlies in less than 20 days, and within a year had blanketed the globe (Rampino and Self 1984). Similarly, the volcanic debris injected into the atmosphere during the eruption of Mount Pinatubo in June 1991, circled the earth at the equator in about 23 days (Gobbi *et al.* 1992). It reached Japan two weeks after the eruption began (Hayashida and Sasano 1993). Within 20 days the edge of the debris cloud had reached southern Europe (Gobbi *et al.* 1992), and less than 2 months later was recognized in the stratosphere above southern Australia (Barton *et al.* 1992). By October of 1991, the cloud was present above Resolute at 74°N in the Canadian Arctic, and by early 1992 had spread worldwide (Rosen *et al.* 1992). Sulphate aerosols and fine ash particles from Mount Hudson which erupted in Chile in August 1991 were carried by strong zonal westerlies between 45°S and 46°S to pass over southeastern Australia within 5 days of the eruption, and around the earth in just over a week (Barton *et al.* 1992).

The build up of the dust veil and its eventual dispersal will depend upon the amount of material ejected during the eruption and the height to which the dust is projected into the atmosphere. The eruption of Krakatoa released at least 6 cubic km (and perhaps as much as 18 cubic km) of volcanic debris into the atmosphere (Lamb 1970). In comparison, Mt St Helens produced only about 2.7 cubic km (Burroughs 1981). Neither of these can match the volume of debris from Tambora, an Indonesian volcano which erupted in 1815, producing an estimated 80 cubic km of ejecta (Findley, 1981). More important than the total particulate production, however, is its distribution in the atmosphere. That depends very much on the altitude to which the debris is carried, and whether or not it penetrates beyond the tropopause. The maximum height reached by dust ejected from Krakatoa has been estimated at 50 km and a similar altitude was reached by the dust column from Mount Agung in 1963 (Lamb 1970). A particularly violent eruption at Bezymianny in Kamchatka, in 1956, threw ash and other debris to a height of 45 km (Cronin 1971), but Mt St Helens, despite the explosive nature of its eruption, failed to push dust higher than 20 km, perhaps because the main force of the explosion was directed horizontally rather than vertically (Findley 1981). As a result, it has been estimated that Mt St Helens injected only 5 million tonnes of debris into the stratosphere compared with 10 million tonnes for Mount Agung, and as much as 50 million tonnes for Krakatoa (Burroughs 1981). The eruptions of El Chichón in 1982 and Mount Pinatubo in 1991 injected an estimated 20 and 30 million tonnes of material respectively into the stratosphere, mostly in the form of sulphur dioxide ($SO_2$) which ultimately produced sulphuric acid aerosols (Brasseur and Granier 1992). In the case of Mount Pinatubo, the amount of $SO_2$ injected was probably as much as that from Krakatoa (Groisman 1992), although the total debris production from the latter was higher.

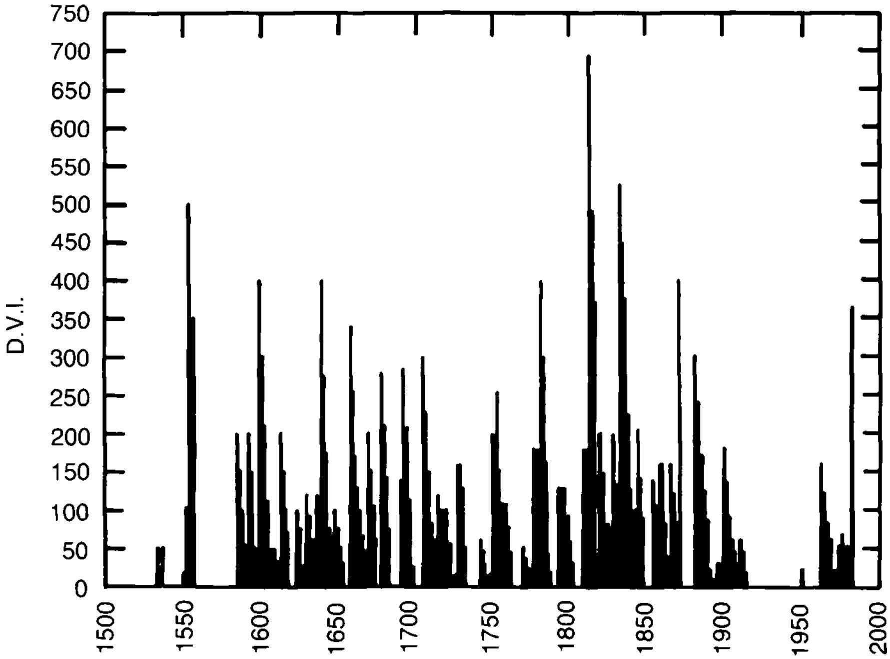
Since the altitude of the tropopause decreases with latitude (see Chapter 2) even relatively minor eruptions may contribute dust to the stratosphere in high latitudes. The dust plume from the Surtsey eruption, off Iceland, in 1963, for example, penetrated the tropopause at 10.5 km (Cronin 1971), whereas the products of a comparable eruption in equatorial regions would have remained entirely within the troposphere. When Nyamuragira in Zaire erupted in 1981, for example, it produced almost as much $SO_2$ as El Chichón, but little of it reached the stratosphere. In contrast, the force of the eruption of Mount Pinatubo penetrated the tropopause at about 14 km, and carried debris up for another 10 to 15 km (Gobbi *et al.* 1992). Particulate matter which is injected into the stratosphere in high latitudes gradually spreads out from its source, but its distribution remains restricted. Most high latitude volcanoes in the northern hemisphere are located in a belt close to the Arctic Circle, and there is no evidence of dust from an eruption in this belt reaching the southern hemisphere (Cronin 1971). In contrast, products of eruptions in equatorial areas commonly spread to form a world-wide dust veil (Lamb 1970). As a result of this, it might be expected that when volcanoes are active in both regions, turbidity in the northern hemisphere would be greater than in the southern. Atmospheric turbidity patterns in the period between 1963 and 1970, when four volcanic plumes in the Arctic Circle belt and three in equatorial regions penetrated the tropopause, tend to confirm the greater turbidity of the northern stratosphere under such conditions (Cronin 1971). There are fewer volcanoes in high latitudes in the southern hemisphere than in the north, but the same restrictions on the distribution of volcanic debris seem to apply. For example, the volcanic ash and sulphuric acid from the eruption of Mount Hudson in southern Chile in 1991 penetrated the tropopause at about 9 km, and was carried around the world quite rapidly on the upper westerlies. However, simulations carried out to estimate the subsequent spread of the debris cloud suggest that it remained restricted to the area between 70°S and 30°S (Barton *et al.* 1992).

## The dust veil index

Individual volcanic eruptions differ from each other in such properties as the amount of dust ejected, the geographical extent of its diffusion and the length of time it remains in the atmosphere. Comparison is possible using these elements, but to simplify the process, and to make it easier to compare the effects of different eruptions on weather and climate, Lamb (1970) developed a rating system which he called a dust veil index (DVI). It was derived using formulae which took into account such parameters as radiation depletion, the estimated lowering of average temperatures, the volume of dust ejected and the extent and duration of the veil. The final scale of values was adjusted so that the DVI for the 1883 eruption of Krakatoa had a value of 1,000. Other eruptions were then compared to that base. The 1963 eruption of Mount Agung was rated at 800, for example, whereas the DVI for Tambora in 1815 was 3,000 (Lamb 1972).

Individual dust veils may combine to produce a cumulative effect when eruptions are frequent (see Figure 5.4). The 1815 eruption of Tambora, for example, was only the worst of several between 1811 and 1818. The net DVI for that period was therefore 4,400. Similarly, Lamb (1972) estimated that between 1694 and 1698, the world DVI was 3,000 to 3,500. At times when volcanic activity is infrequent, the DVI is low, as it was between 1956 and 1963 when no eruptions injected debris into the stratosphere (Lockwood 1979).

*Figure 5.4* Cumulative DVI for the northern hemisphere: dust from an individual eruption is apportioned over 4 years–40% to year 1; 30% to year 2; 20% to year 3 and 10% to year 4




*Source:* From Bradley and Jones (1992)

The DVI provides an indication of the potential disruption of weather and climate by volcanic activity. Dust in the atmosphere reduces the amount of solar radiation reaching the earth's surface, and at high index levels that reduction can be considerable. This is particularly so in higher latitudes where the sun's rays follow a longer path through the atmosphere, and are therefore more likely to be scattered. Major eruptions, producing a DVI in excess of 1,000, have caused reductions in direct beam solar radiation of between 20 and 30 per cent for several months (Lamb 1972). The effect is diminished to some extent by an increase in diffuse radiation, but the impact on net radiation is negative. Observations in Australia, following the eruption of Mount Agung in 1963, showed a maximum reduction of 24 per cent in direct beam solar radiation, yet, because of the increase in diffuse radiation, net radiation fell by only 6 per cent (Dyer and Hicks 1965). Similar values were recorded at the Mauna Loa Observatory in Hawaii at that time (Ellis and Pueschel 1971). El Chichón reduced net radiation by 2–3 per cent at ground level (Pollack and Ackerman 1983), while the reduction caused by Pinatubo averaged 2.7 per cent over a 10-month period following the eruption, with individual monthly values reaching as high as 5 per cent (Dutton and Christy 1992).

A number of problems with the DVI have been identified since it was first developed, and these have been summarized by Chester (1988). The DVI was based solely on dust and did not include the measurement of sulphates or sulphuric acid aerosols, which are now recognized as being very effective at scattering solar radiation. As a result, the impact of sulphur-rich eruptions such as El Chichón or Mount Pinatubo would be underestimated. At the same time, there is no way of preventing non-volcanic sources of dust from being included in the index. The use of climatic parameters in the calculation of certain index values may introduce the possibility of circular reasoning. For example, falling temperatures are taken as an indication of an increasing DVI, yet a high DVI may also be used to postulate or confirm falling temperatures.

In an attempt to deal with some of these problems a number of researchers reassessed Lamb's index, but introduced only limited refinement and modification (Mitchell 1970; Robock 1981). Other indices have also been proposed, although none has been as widely used as the original DVI. One example is the volcanic explosivity index (VEI), developed as a result of research sponsored by the Smithsonian Institute into historic eruptions (Chester 1988). It is based only on volcanological criteria, such as the intensity, dispersive power and destructive potential of the eruption, as well as the volume of material ejected. It also includes a means of differentiating between instantaneous and sustained eruptions (Newhall and Self 1982). Being derived entirely from volcanological criteria, it eliminates some of the problems of the DVI—such as circular reasoning—for example, but it does not differentiate between sulphates and dust, nor does it include corrections for the latitude or altitude of the volcanoes (Chester 1988). Thus, although the VEI is considered by many to be the best index of explosive volcanism, it is not without its problems when used as a tool in the study of climatic change.

A glaciological volcanic index (GVI) has also been proposed (Legrand and Delmas 1987). Based on ice cores, it would reveal acidity levels in glacial ice, and therefore give an indication of the $SO_2$ levels associated with past volcanic eruptions. Since neither the DVI nor the VEI deal adequately with volcanic $SO_2$ emissions, the GVI has the potential to improve knowledge of the composition of volcanic debris. However, current ice core availability is limited, and the GVI adds little to the information available from established indices (Bradley and Jones 1992).

**Volcanic activity, weather and climate**

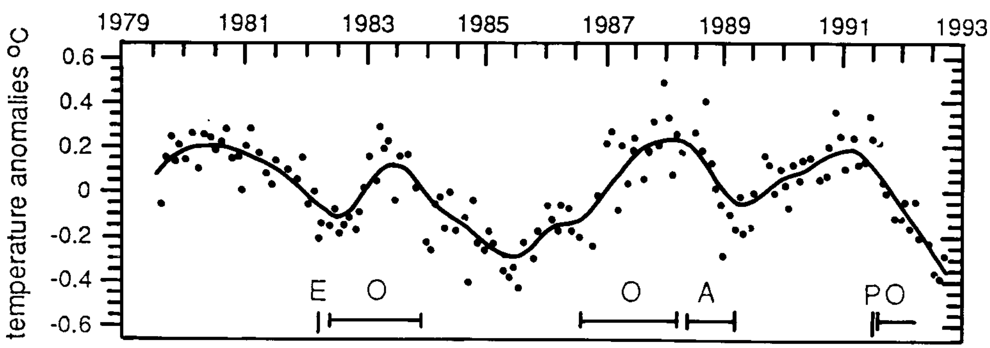
Many of the major volcanic eruptions in historical times have been followed by short-term variations in climate which lasted only as long as the dust veil associated with the eruption persisted. The most celebrated event of this type was the cooling which followed the eruption of Tambora in 1815. It produced in 1816 'the year without a summer', remembered in Europe and North America for its summer snowstorms and unseasonable frosts. Its net effect on world temperature was a reduction of the mean annual value by 0.7°C, but the impact in mid-latitudes in the northern hemisphere was greater, with a reduction of 1°C in mean annual temperature and average summer temperatures in parts of England some 2–3°C below normal (Lamb 1970). The eruption of Krakatoa in 1883 was also followed by lower temperatures which made 1884 the coolest year between 1880 and the present (Hansen and Lebedeff 1988).

Increased volcanic activity may have been a contributing factor in the development of the Little Ice Age—which persisted, with varying intensity from the mid-fifteenth to the midnineteenth century. The eruption of Tambora falls within that time span, and other eruptions have at least a circumstantial relationship with climatic change. A volcanic dust veil may have been responsible for the cool, damp summers and the long, cold winters of the late 1690s in the northern hemisphere, which ruined harvests and led to famine, disease and an elevated death rate in Iceland, Scotland and Scandinavia (Parry 1978). Lamb (1970) has suggested that dust veils were important during the Little Ice Age because their cumulative effects promoted an increase in the amount of ice on the polar seas, which in turn disturbed the general atmospheric circulation. He also points out, however, that contemporaneity between increased volcanic activity and climatic deterioration was not complete. Some of the most severe winters in Europe—such as those in 1607–08 and 1739–40—occurred when the DVI was low, and the period of lowest average winter temperatures did not coincide with the greatest cumulative DVI. Thus, although increased volcanic activity and the associated dust veils can be linked to deterioration between 1430 and 1850, it is likely that volcanic dust was only one of a number of factors which contributed to the development of the Little Ice Age at that time.

Major volcanic episodes in modern times have usually been accompanied by prognostications on their impact on weather and climate, although it is not always possible to establish the existence of any cause and effect relationship. The Agung eruption produced the second largest DVI this century, but its impact on temperatures was less than expected, perhaps because the dust fell out of the atmosphere quite rapidly (Lamb 1970). It is estimated that it depressed the mean temperature of the northern hemisphere by a few tenths of a degree Celcius for a year or two (Burroughs 1981), but such a value is well within the normal range of annual temperature variation. The spectacular eruption of Mt St Helens in 1980—enhanced in the popular imagination by intense media coverage—promoted the expectation that it would have a significant effect on climate, and it was blamed for the poor summer of 1980 in Britain. In comparison to other major eruptions in the past, however, Mt St Helens was relatively insignificant in climatological terms. It may have produced a cooling of a few hundredths of a degree Celcius in the northern hemisphere, where its effects would have been greatest (Burroughs 1981). The eruption of El Chichón in Mexico in 1982 produced the densest aerosol cloud since Krakatoa, nearly a century earlier. Within a year it had caused global temperatures to decline by at least 0.2°C and perhaps as much as 0.5°C (Rampino and Self 1984). However, the cooling produced by El Chichón may have been offset by as much as 0.2°C as the result of an El Niño event which closely followed the eruption, and effectively prevented cooling in the southern hemisphere (Dutton and Christy 1992) (see Figure 5.5). Past experience suggested that the eruption of Mount Pinatubo would also lead to lower temperatures. It was blamed for the cool summer of 1992 in eastern North America, and by September of that year it was linked with reductions in global and northern hemisphere temperatures of 0.5°C and 0.7°C respectively (Dutton and Christy 1992). Estimates by modellers studying world climatic change indicate that such cooling would be sufficient to reverse—at least temporarily—the global warming trends characteristic of the 1980s (Hansen *et al.* 1992).

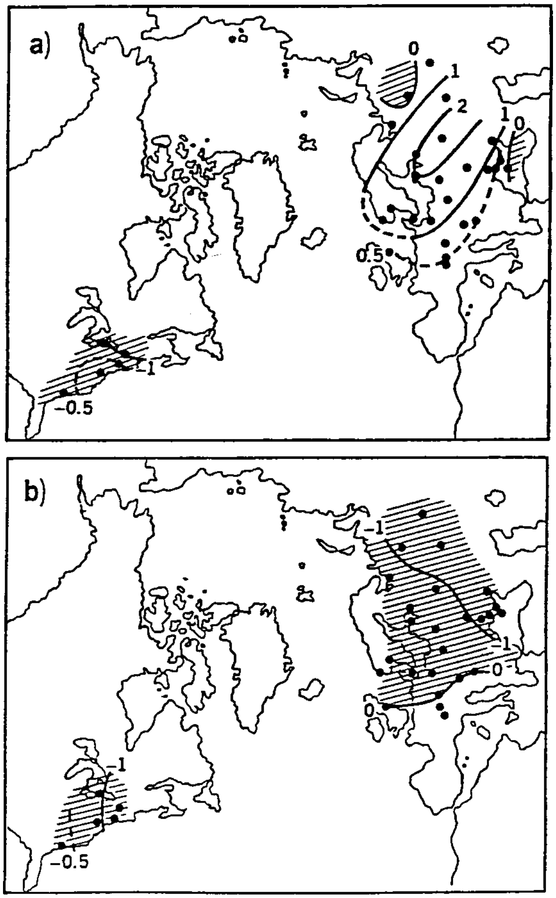
Although volcanic activity is most commonly associated with cooling, there is some evidence that it may also cause short-term, local warming.

*Figure 5.5* Monthly mean global temperature anomalies obtained using microwave sounding units (MSU). The events marked are: A—La Niña; O—El Niño; E—El Chichón; P—Pinatubo




*Source:* After Dutton and Christy (1992)

*Figure 5.6* Mean anomalies of surface air temperature (°C) for the period 2 to 3 years after volcanic eruptions with volcanic explosivity power approximately equal to the Krakatoa eruption, (a) Winter (b) Summer. Points show the stations used. Dashed regions depict n egative anomalies




*Source:* From Groisman (1992)

Groisman (1992) has compared temperature records in Europe and the northeastern United States with major volcanic eruptions between 1815 and 1963. The results show that in western Europe, and as far east as central Russia and Ukraine, statistically significant positive temperature anomalies occur in the winter months some 2 to 3 years after an eruption the size of Krakatoa (see Figure 5.6). The analysis of data following the eruption of El Chichón produced a similar pattern, and Groisman suggests that the unusually mild winter of 1991–92 in central Russia was an indication of a positive anomaly associated with Mount Pinatubo. The warming is seen as a result of the greater frequency of westerly winds over Europe, which owe their development to an increase in zonal temperature gradients following the general global cooling associated with major volcanic eruptions.

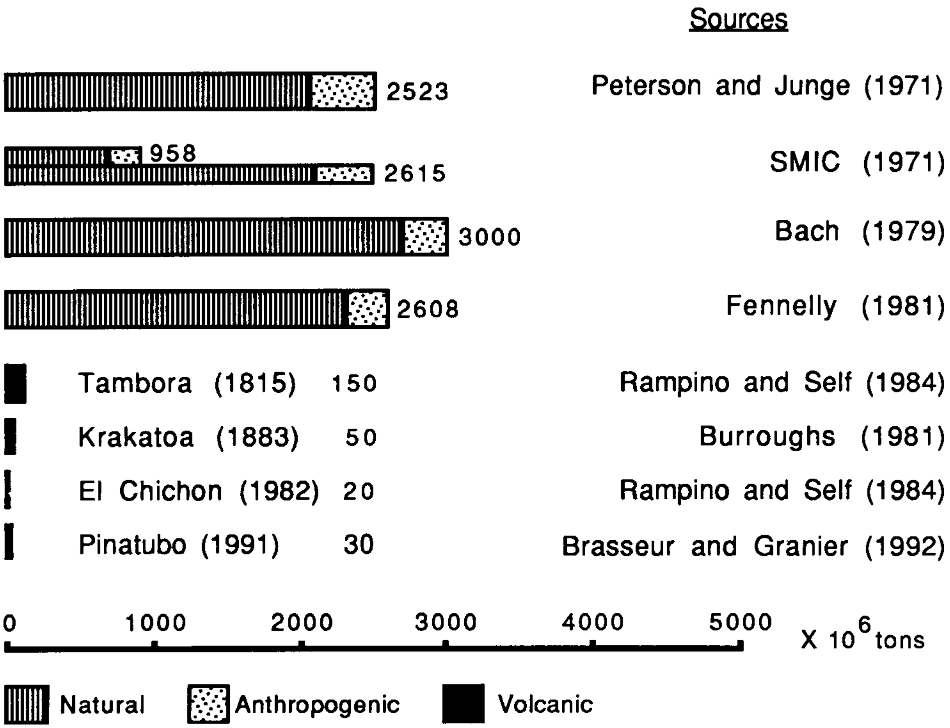
Volcanoes have the ability to contribute to changes in weather and climate at a variety of temporal and spatial scales. At a time when the human input into global environmental change is being emphasized, it is important not to ignore the contribution of physical processes, such as volcanic activity, which have the ability to augment or diminish the effects of the anthropogenic disruption of the earth/atmosphere system.

## THE HUMAN CONTRIBUTION TO ATMOSPHERIC TURBIDITY

The volume of particulate matter produced by human activities cannot match the quantities emitted naturally (see Figure 5.7). Estimates of the human contribution to total global particulate production vary from as low as 10 per cent (Bach 1979) to more than 15 per cent (Lockwood 1979) with values tending to vary according to the size-fractions included in the estimate. Human activities may provide as much as 22 per cent of the particulate matter finer than 5 μm, for example (Peterson and Junge 1971). It might be expected that the human contribution to atmospheric turbidity would come mainly from industrial activity in the developed nations of the northern hemisphere, and that was undoubtedly the case in the past, but data from some industrialized nations indicate that emissions of particulate matter declined in the 1980s (see Figure 5.8). There is also some evidence that the burning of tropical grasslands is an important source of aerosols (Bach 1976), and although specific volumes are difficult to estimate, smoke and soot released during the burning of tropical

*Figure 5.7* A comparison of natural and anthropogenic sources of particulate matter

*Note:* The volcanic contributions appear small. Their major impact is produced by their ability to make a rapid and intense contribution to the aerosol content of the atmosphere.

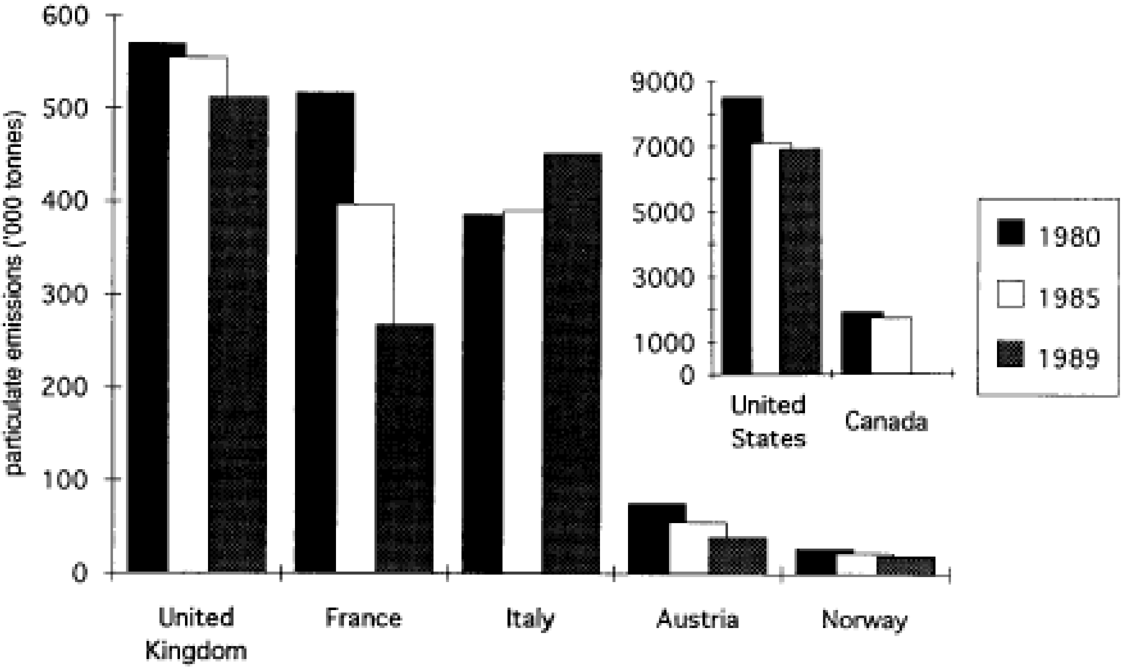



rainforests must make a significant contribution to turbidity. Some authorities would also include soil erosion—created by inefficient or destructive agricultural practices—among anthropogenic sources of aerosols (Lockwood 1979). Anthropogenically generated particulate matter tends to remain closer to the earth's surface than the natural variety, as is readily apparent in most large urban areas. One of the few exceptions is the direct injection of soot particles into the stratosphere by high-flying commercial aircraft. The annual production of elemental carbon from that source is estimated at 16,000 tonnes, of which 10 per cent is added directly to the stratosphere. With the introduction of a new generation of supersonic aircraft—which would spend a greater proportion of their flight time in the stratosphere—stratospheric soot loading would probably double (Pueschel *et al.* 1992).

Various attempts have been made to estimate the impact of human activities on background levels of atmospheric turbidity. One approach to this is to examine turbidity levels in locations such as the high Alps and the Caucasus (renowned for their clean air) or mid-ocean and polar locations (far removed from the common sources of aerosols). These are seen as reference points from which trends can be established. As it stands, the evidence is remarkably contradictory.

There are data which support the view that human activities are enhancing global aerosol levels. A set of observations from Davos in Switzerland suggests an 88 per cent increase in turbidity in the thirty years up to the mid-1960s (McCormick and Ludwig 1967), and dustfall in the Caucasus Mountains showed a rapid increase during a similar time span (Bryson 1968). At Mount St Katherine, over 2,500 m up into the

*Figure 5.8* Emissions of particulate matter from selected nations: 1980–89

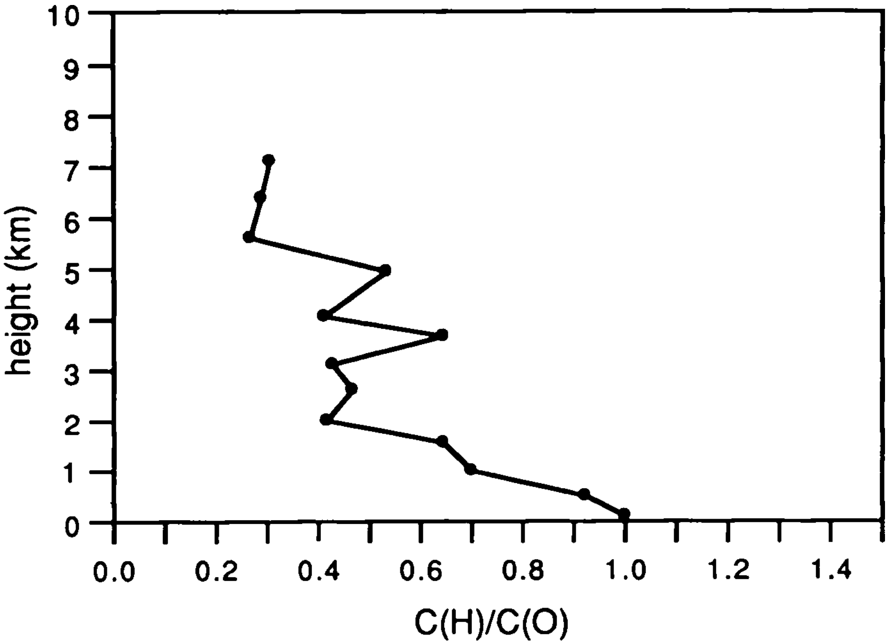



*Source:* Based on data in World Resources Institute (1992)

atmosphere in the Sinai, measurements indicate a 10 per cent reduction in direct beam solar energy up to the mid-1970s, in an area far removed from major industrial sources (Lockwood 1979). The fine particle content of the air above the North Atlantic doubled between 1907 and 1969, and at Mauna Loa in Hawaii, one estimate suggests an increase in turbidity of 30 per cent in the ten years between 1957 and 1967 (Bryson 1968). That period included the Mount Agung eruption, but the increase was still apparent after the effects of the volcanic emissions had been removed from the calculations (Bryson and Peterson 1968). On the assumption that natural background levels of atmospheric turbidity should remain constant, or fluctuate within a very narrow range, these rising aerosol levels were ascribed to human activities.

The development of the Arctic Haze in recent years is generally considered to be an indication of continuing anthropogenic aerosol loading of the atmosphere. The haze is not of local origin. It is created in mid-latitudes as atmospheric pollution, which is subsequently carried polewards to settle over the Arctic. It is most pronounced between December and March, for several reasons, including the increased emission of pollutants at that season, the more rapid and efficient poleward transport in winter and the longer residence time of haze particles in the highly stable Arctic air at that time of year (Shaw 1980). Vertical profiles through the air mass show that the bulk of the aerosols are concentrated in the lowest 2 km of the atmosphere (see Figure 5.9). Arctic air pollution has increased since the mid-1950s in parallel with increased aerosol emissions in Europe, and the net result has been a measurable reduction in visibility and perturbation of the regional radiation budget (Barrie 1986).

*Figure 5.9* An estimate of the mean vertical profile of the concentration of anthropogenic aerosol mass in the high Arctic during March and April




*Source:* After Barrie (1986)
*Note:* C(H)/C(0) is the concentration at a specific altitude divided by the concentration at the surface.

Arctic Haze includes a variety of components—from dust and soot particles to pesticides—but the most common constituent is sulphate particles. Their presence at increasingly high concentrations not only in the Arctic, but in other remote areas, such as the republic of Georgia in the former Soviet Union, far removed from major pollution sources, is also causing concern (Shaw 1987), because of their ability to disrupt the flow of energy in the atmosphere and because of the contribution they make to acid precipitation (see Chapter 4).

Providing a direct contrast to these developments are studies which claim that it is not possible to detect any human imprint in changing atmospheric turbidity. Observations in the Antarctic in the mid-1960s revealed no significant change in aerosol levels in that area between 1950 and 1966 (Fischer 1967). Data from Mauna Loa, where Bryson and Peterson (1968) claimed to find evidence of rising levels of turbidity induced by human activities, were re-interpreted to show that there was no evidence that human activity affected atmospheric turbidity on a global scale (Ellis and Pueschel 1971). The short term fluctuations revealed in the data were associated with naturally produced aerosols. The contradictory results from Mauna Loa reflect differences in the scientific interpretation of the data from one observatory. Differences between stations are the result of a combination of physical and human factors, and, in reality, are only to be expected. Emission sites are unevenly distributed. Most are located in mid-latitudes in the northern hemisphere, and there are great gaps—over the oceans, for example—where little human activity takes place. The atmospheric circulation helps to spread the pollutants, but, since the bulk of the emissions from anthropogenic sources are confined to the lower troposphere, their residence time in the atmosphere is relatively short. Their eventual distribution is therefore less widespread than volcanic emissions—which are concentrated in the upper troposphere and stratosphere. Aerosols produced in the industrial areas of the northeastern United States have almost entirely dropped out of the westerly air-stream before it reaches Europe, but aerosols from European sources spread over most of North Africa in January, and may drift out over the Atlantic also, depending upon the strength of the continental high pressure system (Lockwood 1979). Such patterns may help to explain the rising turbidity levels in the Alps and the Caucasus, and even in the Sinai. In the southern hemisphere, the particulate contribution from industrial activity is negligible, and there is only limited cross-equatorial flow from the north. Aerosols produced during the burning of tropical forests and grasslands will offset the reduction in industrial aerosols (Bach 1976), but the proportion of aerosols of direct anthropogenic origin is usually considered to be much less than in the northern hemisphere. The absence of anthropogenic aerosol sources may explain the lack of change in turbidity over the Antarctic, but the presence of high pressure at the surface and the strong westerlies of the circumpolar vortex aloft may combine to prevent the transport of aerosols into the area. This is certainly the case with natural aerosols. Particulate matter from Pinatubo and Mount Hudson was unable to penetrate the Antarctic circumpolar vortex during the first winter following its emission (Deshler *et al.* 1992). The exact contribution of anthropogenic sources of aerosols to atmospheric turbidity is difficult to determine, and is likely to remain so until the number of measuring sites is increased and their current uneven distribution is improved.

## THE KUWAIT OIL FIRES

In the final stages of the Gulf War in February 1991 between 500 and 600 oil wells were set alight by the retreating Iraqi army. These wells continued to burn for several months, kept alight by oil and gas brought to the surface under pressure from the underlying oil fields. During that time they added massive amounts of smoke, sulphur dioxide, carbon dioxide, unburned hydrocarbons and oxides of nitrogen to the atmosphere. Most of these products were confined to the lower half of the troposphere, with the top of the plume never exceeding 5 km. At the height of the fires it was estimated that sulphur dioxide was being added to the atmosphere at an equivalent rate of 6.1 million tonnes per year, and soot at 6.4 million tonnes per year (Johnson *et al.* 1991). Although most of the original emissions were retained in the region as the result of stable air masses, those aerosols that had reached higher in the atmosphere were carried northeastwards bringing acid rain to Iran and black snow to the mountains of Pakistan. Several months later, unexpectedly high levels of carbon soot in the upper troposphere above Japan were also identified as products of the oil fires (Okada et al. 1992).

With particulate mass densities of 500–1,000 $\mu gm^{-3}$, the impact of the pollution cloud on incoming solar radiation was spectacular. Beneath the centre of the plume the shortwave radiation flux was measured at zero (Johnson *et al.* 1991). This led to daytime temperature reductions beneath the cloud of as much as 5.5°C (Seager 1991), and although some infrared radiation was returned from the cloud it did little to ameliorate the cooling. Mean monthly temperatures between March and September were reduced by 0.8 to 2.4°C, and record low mean monthly temperatures were established in July and August (Shaw 1992). With large amounts of energy being intercepted by the plume and absorbed by the soot particles, the plume itself warmed up. In earlier assessments of the impact of the oil fires it was suggested that such internal heating would be sufficient to cause lofting of aerosols into the stratosphere, which would in turn increase the climatic consequences of the fires (Pearce 1991a). This did not happen, however, perhaps because of the low altitude of the initial plume, and the rapidity with which the fires were extinguished. As a result, although the fires had a regional climatic impact, the global prognostications, which included the failure of the Asian summer monsoon, did not come to pass (Pearce 1991a; Johnson *et al.* 1991).

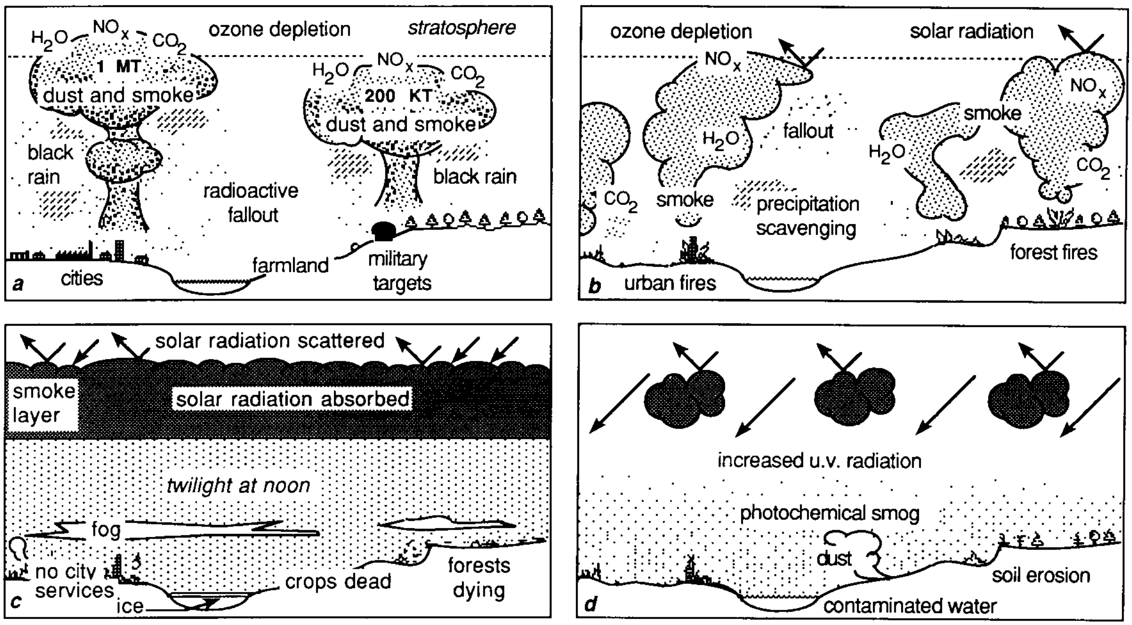
## NUCLEAR WINTER

The Kuwait oil field fires provided the atmosphere with probably the greatest amount of anthropogenically generated aerosols ever produced by a single event, and to a number of observers they shared similarities with the major fires expected to follow a nuclear war (Pearce 1991 a). Urban fires, for example, with ready access to smoke producing wood, paper, plastics and fossil fuels would produce similar combustion products. The fires likely to be ignited by nuclear explosions were estimated to be much larger in scale, however, capable of adding more than 200 million tonnes of smoke to the atmosphere over several weeks (Turco *et al.* 1983). Together with the estimated 960 million tonnes of dust expected to be injected into the atmosphere by the initial nuclear explosions this would increase the turbidity of the atmosphere to such an extent that major global cooling would take place (see Figure 5.10).

The concept of nuclear winter grew out of a study of the climatic consequences of nuclear war published by Turco *et al.* in 1983. The study postulated that a major nuclear conflict would be followed by a very rapid cooling of the earth, sufficient to cause temperatures to fall below freezing in some areas even in mid-summer. Because such an event would reduce temperatures to winter levels, even after a midsummer war, it was given the name *nuclear winter,* and the work became known as the TTAPS study from the first letters of the names of the investigators.

The TTAPS hypothesis was based on the assumption that smoke and dust thrown into the atmosphere during a nuclear war would increase atmospheric turbidity to such an extent that a high proportion of incoming solar radiation would be prevented from reaching the earth's

*Figure 5.10* The development of nuclear winter: (a) the conflict; (b) post-conflict fires; (c) nuclear winter; (d) the after-effects



surface. The net effect would be to drive temperatures down. Since none of this could be measured directly, estimates were based on the results of a series of mathematical simulation models.

According to the TTAPS baseline scenario, a 5,000 megatonne nuclear war would inject 960 million tonnes of dust into the atmosphere (1 megatonne is equivalent to 1 million tonnes of TNT). Eighty per cent would reach the stratosphere, and remain there for more than a year. This dust veil would be augmented by as much as 225 million tonnes of smoke, produced over a period of several weeks by the massive fires ignited by the initial explosions. Incorporated into the atmospheric circulation, the dust and smoke would first spread over the northern hemisphere—where it was assumed most of the nuclear explosions would take place—before being carried into the southern hemisphere, eventually to blanket the entire globe.

The net result of this massive increase in atmospheric turbidity would be the reduction of incoming solar radiation by as much as 95 per cent, causing an average land surface cooling of 10–20°C and maximum cooling of up to 35°C in the the interior of the continents in a matter of weeks. The temperature reductions over the oceans and in coastal areas would be perhaps only 1–3°C because the cooling would be offset by the great heat capacity of the oceans. The juxtaposition of these relatively mild conditions with the cold over the land masses would create strong horizontal temperature and pressure gradients and lead to severe coastal storms. Changes in the vertical temperature structure of the atmosphere, induced by the absorption of large amounts of solar energy in the upper atmosphere, would also contribute to a much modified global circulation. It was estimated that recovery from all of these changes would take more than a year. The potential environmental impact of gases such as $CO_2$ and $NO_X$, released into the atmosphere along with the particulate matter, was recognized, and the biological consequences of nuclear winter were noted, but neither was elaborated.

The TTAPS hypothesis elicited a strong response from the scientific community. The assumptions underlying the estimated endurance and intensity of the smoke and dust clouds were strongly criticized, for example, and the magnitude of the postulated temperature decline was regarded as questionable (see e.g. Maddox 1984; Singer 1984). Much of this initial criticism merely detailed perceived flaws in the study itself, and did little to develop the concept or to invalidate it (Teller 1984).

Other investigators examined the mechanics of the study, and replaced its simplistic one-dimensional atmospheric model with two- and three-dimensional versions. The state-of-the-art, 3-D, general circulation models (GCMs) ultimately used included a greater number of variables and finer geographic resolution than the TTAPS model, and incorporated earth/atmosphere feedback loops. In general they indicated that planetary cooling would be much less than postulated in the TTAPS scenario, and it was suggested that the cooling following a nuclear war would be more appropriately referred to as 'nuclear autumn' (or 'nuclear fall') than nuclear winter (Thompson and Schneider 1986).

The environmental consequences of nuclear war (ENUWAR) received little attention in the TTAPS scenario, but a contemporary study by a group of life scientists indicated that the net effect of a large scale nuclear war would be the global disruption of the biosphere, and the disruption of the biological support systems of civilization (Ehrlich *et al.* 1983) (see Figure 5.11). The severity of the impact has been mitigated in line with the successive modifications of the nuclear winter hypothesis, but the situation is still considered serious. The report of the Scientific Committee on Problems of the Environment (SCOPE) concerning the ecological and agricultural impact of nuclear war (Harwell and Hutchinson 1985) sponsored by the International Council of Scientific Unions (ICSU) identified indirect biological effects as a major threat to society, and subsequent studies by the SCOPE-ENUWAR researchers have confirmed this

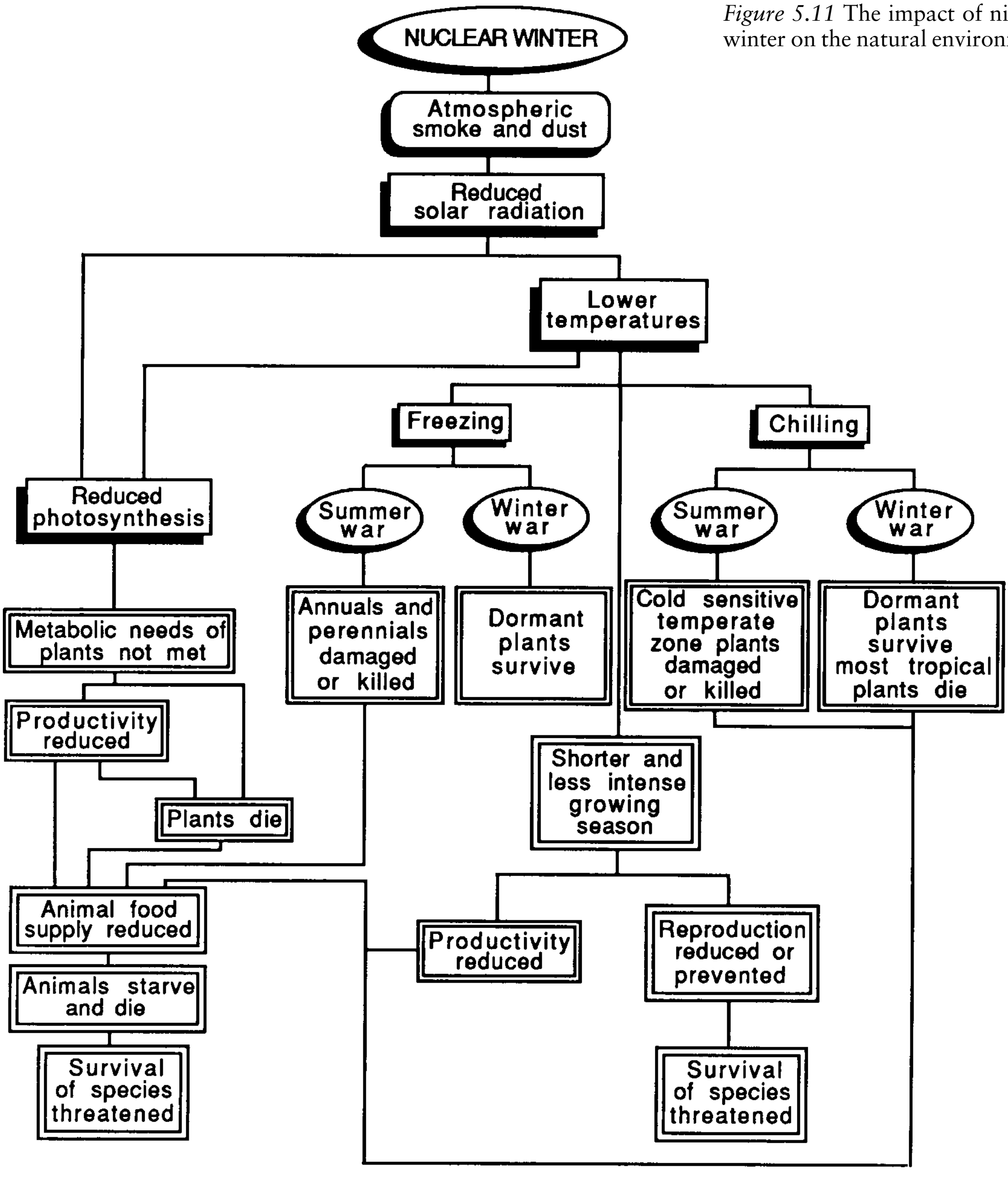



*Figure 5.11* The impact of niclear winter on the natural environment

(SCOPE-ENUWAR 1987; Appleby and ments Harrison 1989).

The original TTAPS team has re-examined nuclear winter in light of the new information available from laboratory studies, field experiand numerical modelling (Turco *et al.* 1990). While areas of uncertainty remain the new research reaffirms the basic findings of the original work, including the cooling estimates upon which nuclear winter was based.

## COOLING OR WARMING?

In the mid-1970s, increasing atmospheric turbidity associated with human activity was considered to be one of the mechanisms capable of inducing global cooling (Calder 1974; Ponte 1976). The processes involved seemed plausible and logical, at least in qualitative terms. The introduction of pollutants into the atmosphere, at a rate greater than they could be removed by natural processes, would allow the progressive build up of aerosols until sufficient quantities had accumulated to cause a rise in global turbidity levels. The net result would be a reduction in insolation values at the earth's surface as more of the direct beam solar radiation was scattered or reflected by the particulate matter in the atmosphere. The ability of some of the aerosols to act as condensation nuclei would also tend to increase cloudiness and further reduce the receipt of insolation. It has been estimated that natural aerosols in the troposphere probably reduce global surface temperatures by about 1.5°C (Toon and Pollack 1981), and results obtained by atmospheric modelling techniques suggest that a doubling of the atmospheric aerosol content would reduce surface temperature by up to 5°C (Sellers 1973). Global cooling following major volcanic eruptions would tend to support such estimates, and other natural events, such as forest fires, have been linked with regional cooling. Wildfires in Alberta, Canada in 1982 reduced average daytime temperatures in the north-central United States by 1.5–4.0°C, and fires in China in 1987 were followed by reductions of 2.0–6.0°C in daytime temperatures in Alaska (Appleby and Harrison 1989). The local cooling in the Middle East at the height of the Kuwait oil fires also fits this pattern.

No realistic value for the impact of anthropogenic aerosols on global temperatures is available. It has been estimated that a 3 to 4 per cent increase in global turbidity levels would be sufficient to reduce the mean temperature of the earth by 0.4°C, and, according to proponents of anthropogenically produced dust as a factor in climatic change—such as Reid Bryson (1968)—this would be enough to account for the global cooling which took place between 1940 and 1960. Results such as these were based on the observation that global cooling often followed major volcanic eruptions. Particulate matter produced by human activity was considered equivalent to volcanic dust and, therefore, capable of contributing directly to global cooling. In addition, by elevating background turbidity levels, it allowed smaller volcanic eruptions to be more effective in producing climatic change (Bryson 1968). This comparison of aerosols of human and volcanic origin has been questioned, however (Kellogg 1980; Toon and Pollack 1981). Most particulate matter injected into the atmosphere during human activities does not rise beyond the tropopause. As a result its residence time is limited, and its impact is confined to an area commonly between 1,000 and 2,000 km downwind from its source (Kellogg 1980). Most sources of anthropogenic aerosols are on land, and there the addition of particles to the boundary layer tends to reduce the combined albedo of the surface and the lower atmosphere. The reduced reflection of incoming radiation then promotes warming. The opposite effect is experienced over the oceans, where the combined albedo is increased, producing greater reflectivity and therefore cooling (Bolle *et al.* 1986). Differential changes such as these might in time alter local circulation patterns through their influence on atmospheric stability.

Little anthropogenically produced particulate matter enters the stratosphere at present, but, should that change, the effects would be greater and more prolonged than those produced by the tropospheric aerosols (Bolle *et al.* 1986). Stratospheric aerosols alter the energy budget in two ways. They scatter, reflect and, to a lesser extent, absorb incoming solar radiation which reduces the amount of energy reaching the earth's surface and contributes to cooling. They also absorb outgoing terrestrial infrared radiation. The net result is a warming of the stratosphere. Information on the warming ability of anthropogenic aerosols is not readily available, but the aerosols ejected by Mount Pinatubo raised stratospheric temperatures by between 3.5 and 7°C (McCormick 1992; Gobbi *et al.* 1992). Some of the energy trapped in this way will be reradiated back towards the earth's surface, but most will be lost into space, particularly if the aerosols have been injected to high levels in the stratosphere (Lacis *et al.* 1992). As the particles begin to sink, however, the zone of warming will be brought closer to the surface, and an increased proportion of the energy radiated from it will reach the troposphere, helping to offset the cooling. The warming of the stratosphere will also intensify the stratospheric temperature inversion, creating greater stability and reducing the vigour of the atmospheric circulation. Experiments with GCMs suggest that an increase in particulate matter in the stratosphere would dampen the Hadley circulation (see Chapter 2), slowing down the easterlies in the tropics and the westerlies in the sub-tropics (Bolle *et al.* 1986). However, from their studies of the Mount Pinatubo aerosols, Brasseur and Granier (1992) have estimated that the stratospheric warming following the eruption strengthened the mean meridional circulation by approximately 10 per cent.

Records from which anthropogenically generated aerosol trends can be determined are sparse, and estimates of their impact have been developed mainly through theoretical study rather than by direct observation in the atmosphere. In reality, it is not yet possible to prove that human activities have or have not induced climatic change through the release of aerosols, nor is it possible to make realistic future projections. The SMIC Report (1971) recognized the ability of particulate matter in the atmosphere to cause warming, but suggested that it was insufficient to compensate for the cooling caused by the attenuation of solar radiation. In contrast, some estimates suggest that it is possible that the net effect of elevated atmospheric aerosol levels could be a slight warming, rather than a cooling (Bach 1979).

Atmospheric turbidity has received less attention from academics and the media in recent years. Perhaps the success of local air pollution control measures has helped to reduce the general level of anxiety. In the early 1970s, it seemed possible that anthropogenic aerosols would increase turbidity sufficiently to cause global cooling, and possibly contribute to the development of a new Ice Age (Calder 1974). Concern for cooling has been replaced by concern over global warming, mainly as a consequence of the intensification of the greenhouse effect (see Chapter 7). It has been argued that the presence of particulate matter in the atmosphere has tempered the impact of the greenhouse effect (Bryson and Dittberner 1976), but it now appears possible that under some conditions aerosols actually add to the warming (Bach 1979). Kellogg (1980) has suggested that, on a regional scale, the warming effect of aerosols is more important than the effect of increased carbon dioxide, although, on a global scale, the situation is reversed. He also points out that efforts to control air pollution in industrial areas will ensure that aerosol effects will decline while the impact of the greenhouse effect will continue to grow. Similar issues are considered by Charlson *et al.* (1992) in their examination of climate forcing by anthropogenic aerosols in the troposphere. They claim that current levels of anthropogenic sulphate particles are sufficiently high to offset substantially the global warming produced by greenhouse gas forcing, but acknowledge the many uncertainties which remain to be resolved.

The lack of solid data means that many questions involving the impact of atmospheric turbidity on climate remain inadequately answered. The extent of the human contribution to atmospheric turbidity is still a matter of speculation. Air pollution monitoring at the local and regional level provides data on changing concentrations of particulate matter over cities and industrial areas, but there is as yet insufficient information to project these results to the global scale. In studying the impact of turbidity on climate, most of the work has dealt with temperature change, but it is also possible that aerosols influence precipitation processes, because of their ability to act as condensation nuclei. The extent and direction of that influence is largely unknown. A general consensus appeared to emerge in the mid-1980s, that changes in climate brought on by increasing aerosol concentrations have been relatively minor, taking the form of a slight warming rather than the cooling postulated a decade earlier. It is entirely possible, however, that in the event of a significant global temperature reduction at some time in the future, atmospheric turbidity will be resurrected as a possible cause. The development of new, improved GCMs will help to provide information on the climatic effects of atmospheric aerosols, but it is recognized by the World Meteorological Organization, and a number of other international scientific and environmental groups, that direct atmospheric observation and monitoring is essential if the necessary aerosol climatology is to be established (Kellogg 1980; Bolle *et al.* 1986).

## SUMMARY

Particulate matter has undoubtedly been a constituent of the atmosphere from the very beginning, and natural processes which existed then continue to make the major contribution to atmospheric turbidity. Volcanic activity, dust storms and a variety of physical and organic processes provide aerosols which are incorporated into the gaseous atmosphere. Human industrial and agricultural activities also help to increase turbidity levels. The aerosols vary in size, shape and composition from fine chemical crystals to relatively large, inert soil particles. Once into the atmosphere, they are redistributed by way of the wind and pressure patterns, remaining in suspension for periods ranging from several hours to several years, depending upon particle size and altitude attained. The presence of aerosols disrupts the inward and outward flow of energy through the atmosphere. Studies of periods of intense volcanic activity suggest that the net effect of increased atmospheric turbidity is cooling, and some of the coldest years of the Little Ice Age—between 1430 and 1850—have been correlated with major volcanic eruptions. Aerosols produced by human activities cannot match the volume of material produced naturally, but, in the 1960s and early 1970s, some studies suggested that the cumulative effects of relatively small amounts of anthropogenic aerosols could also cause cooling. Present opinion sees atmospheric turbidity actually producing a slight warming. The greatest problem in the study of the impact of atmospheric turbidity on climate is the scarcity of appropriate data and that situation can only be changed by the introduction of systematic observation and monitoring, to complement the theoretical analysis—based on atmospheric modelling techniques—which has been developed in recent years.

## SUGGESTIONS FOR FURTHER READING

Royal Meteorological Society (1992) ‘Gulf War Meteorology: Special Issue’, *Weather* 47(6), London: Royal Meteorological Society.

Sagan, C. and Turco, R. (1990) *A Path Where No Man Thought: Nuclear Winter and the End of the Arms Race,* New York: Random House.

# 6

# The threat to the ozone layer

One of the most important functions of the atmosphere is to provide the surface of the earth with protection from solar radiation. This may seem contradictory at first sight, since solar radiation provides the energy which allows the entire earth/atmosphere system to function. As with most essentials, however, there are optimum levels beyond which a normally beneficial input becomes harmful. This is particularly so with the radiation at the ultraviolet end of the spectrum (see Table 6.1). At normal levels, for example, it is an important germicide, and is essential for the synthesis of Vitamin D in humans. At elevated levels it can cause skin cancer, and produce changes in the genetic make-up of organisms. In addition, since ultraviolet radiation is an integral part of the earth's energy budget, changes in ultraviolet levels have the potential to contribute to climatic change.

Under normal circumstances, a layer of ozone gas in the upper atmosphere keeps the ultraviolet rays within manageable limits. Close to the equator, ozone allows only 30 per cent of the ultraviolet-B (UV-B) radiation to reach the surface. A comparable value for higher latitudes is about 10 per cent, although during the summer months radiation receipts may approach equatorial levels (Gadd 1992). Specific amounts vary in the short-term with changes in such factors as cloudiness, air pollution and natural fluctuations in ozone concentrations. Ozone is a relatively minor constituent of the atmosphere. It is diffused through the stratosphere between 10 and 50 km above the surface, reaching its maximum concentration at an altitude of 20 to 25 km. If brought to normal pressure at sea-level, all of the existing atmospheric ozone would form a band no more than 3 mm thick (Dotto and Schiff 1978). This small amount of a minor gas, with an ability to filter out a very high proportion of the incoming ultraviolet radiation, is essential for the survival of life on earth. It removes most of the extremely hazardous UV-C wavelengths and between 70 and 90 per cent of the UV-B rays (Gadd 1992). The amount of ozone in the upper atmosphere is not fixed; it may fluctuate by as much as 30 per cent from day to day and by 10 per cent over several years (Hammond and Maugh 1974). Such fluctuations are to be expected in a dynamic system, and are kept under control by built-in checks and balances. By the early 1970s, however, there were indications that the checks and balances were failing to prevent a gradual decline of ozone levels. Inadvertent human interference in the chemistry of the ozone layer was identified as the cause of the decline, and there was growing concern over the potentially disastrous consequences of

*Table 6.1* Different forms of ultraviolet radiation

| *Radiation* | *Wavelength* |
| --- | --- |
| ultraviolet-A (UV-A) | 320–400 nm |
| ultraviolet-B (UV-B) | 280–320 nm |
| ultraviolet-C (UV-C) | 200–280 nm |

1 nm (nanometre)=$1\times10^{-9}$m=$1\times10^{-3}$μm

elevated levels of ultraviolet radiation at the earth's surface. The depletion of the ozone layer became a major environmental controversy by the middle of the decade. Its technological complexity caused dissension in scientific and political arenas, and—with more than a hint of science fiction in its make-up—it garnered lots of popular attention. In common with many environmental concerns of that era, however, interest waned in the late 1970s and early 1980s, only to be revived again with the discovery in 1985 of what has come to be called the Antarctic ozone hole.

## THE PHYSICAL CHEMISTRY OF THE OZONE LAYER

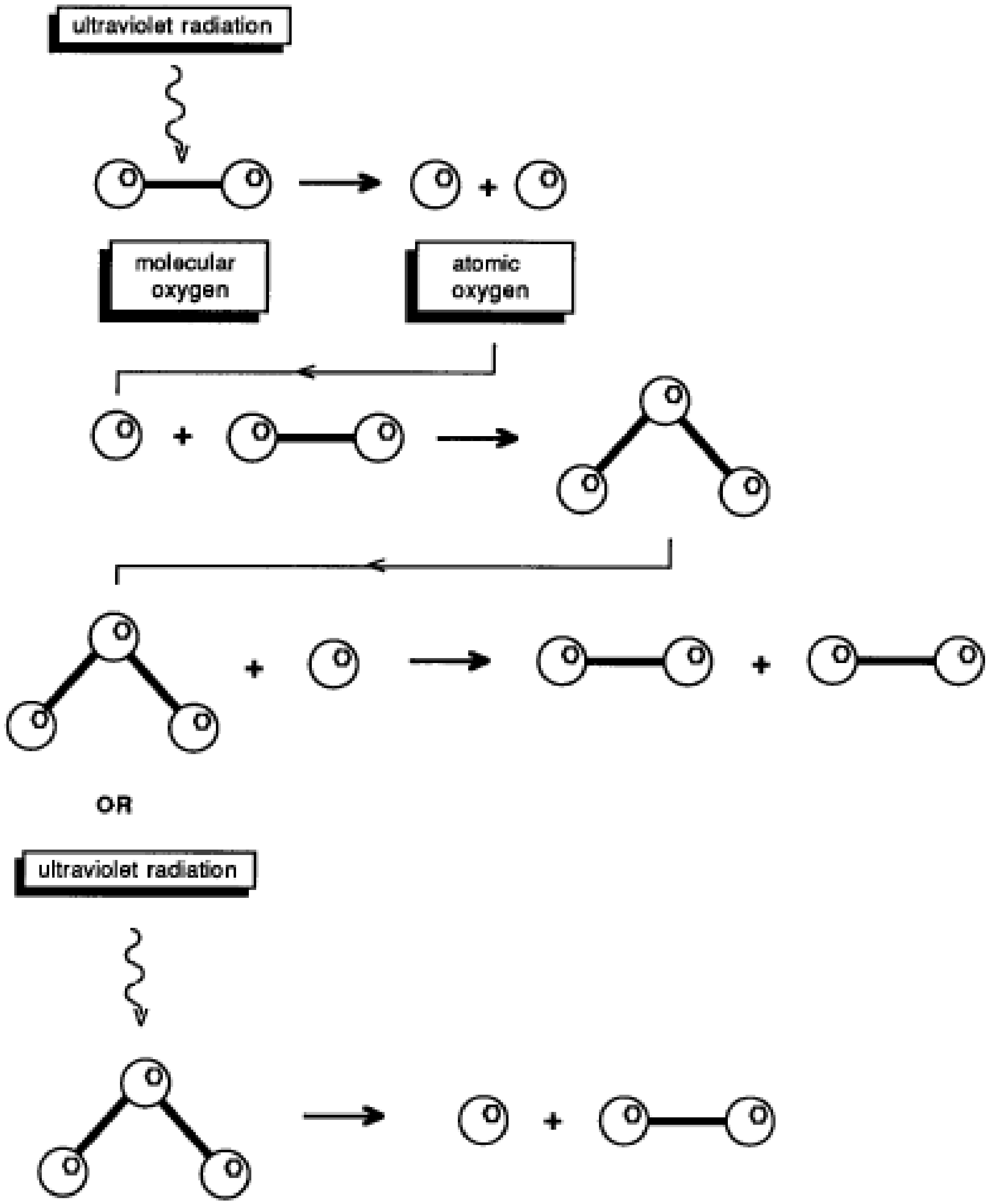
Ozone owes its existence to the impact of ultraviolet radiation on oxygen molecules in the stratosphere, with the main production taking place in tropical regions where radiation levels are high (Rodriguez 1993). Oxygen molecules normally consist of two atoms, and in the lower atmosphere they retain that configuration. At the high energy levels associated with ultraviolet radiation in the upper atmosphere, however, these molecules split apart to produce atomic oxygen (see Figure 6.1). Before long, these free atoms combine with the available molecular oxygen to create triatomic oxygen or ozone. That reaction is reversible. The ozone molecule may break down again into its original components, molecular oxygen and atomic oxygen, as a result of further absorption of ultraviolet radiation, or it may combine with atomic oxygen to be reconverted to the molecular form (Crutzen 1974). The total amount of ozone in the stratosphere at any given time represents a balance between the rate at which the gas is being produced and the rate at which it is being destroyed. These rates are directly linked; any fluctuation in the rate of production will be matched by changes in the rate of decay until some degree of equilibrium is attained (Dotto and Schiff 1978). Thus, the ozone layer is in a constant state of flux as the molecular structure of its constituents changes.

The role of ultraviolet radiation and molecular oxygen in the formation of the ozone layer was first explained by Chapman in 1930. Later measurement indicated that the basic theory was valid, but observed levels of ozone were much less than expected, given the rate of decay possible through natural processes. Since none of the other normal constituents of the atmosphere, such as molecular oxygen, nitrogen, water vapour or carbon dioxide was considered capable of destroying the ozone, attention was eventually attracted to trace elements in the stratosphere. Initially, it seemed that these were present in insufficient quantity to have the necessary effect, but the problem was solved with the discovery of catalytic chain reactions in the atmosphere (Dotto and Schiff 1978). A catalyst is a substance which facilitates a chemical reaction, yet remains itself unchanged when the reaction is over. Being unchanged, it can go on to promote the same reaction again and again, as long as the reagents are available, or until the catalyst itself is removed. In this form of chain reaction, a catalyst in the stratosphere may destroy thousands of ozone molecules before it is finally removed. The ozone layer is capable of dealing with the relatively small amounts of naturally occurring catalysts. Recent concern over the thinning of the ozone layer has focused on anthropogenically produced catalysts (see Figure 6.2), which were recognized in the stratosphere in the early 1970s, and which have now accumulated in quantities well beyond the system's ability to cope.

## NATURALLY OCCURRING, OZONE DESTROYING CATALYSTS

Natural catalysts have probably always been part of the atmospheric system, and many—such as hydrogen, nitrogen and chlorine oxides—are similar to those now being added to the atmosphere by human activities. The main difference is in production and accumulation. The natural catalysts tend to be produced in smaller quantities and remain in the atmosphere for a

*Figure 6.1* Schematic representation of the formation of stratospheric ozone

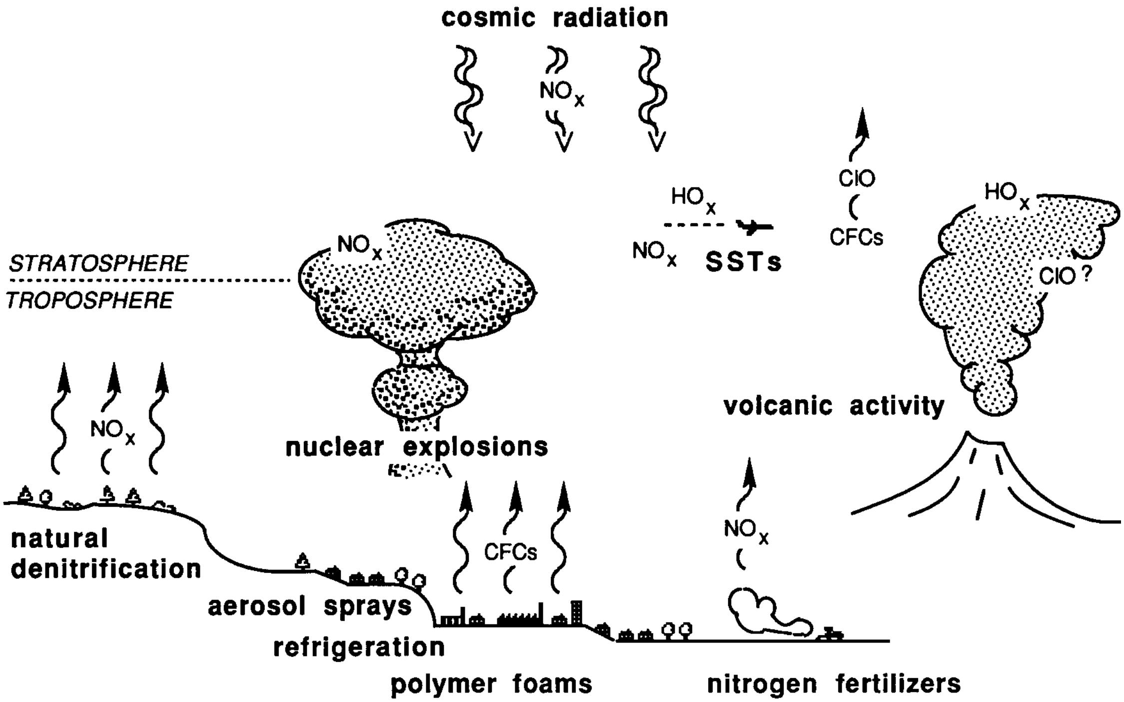



shorter time than their anthropogenic counterparts.

### Hydrogen oxides

Hydrogen oxides ($HO_X$) include atomic hydrogen, the hydroxyl radical (OH) and the perhydroxyl radical ($HO_2$)—all derived from water vapour ($H_2O$), methane ($CH_4$) and molecular hydrogen ($H_2$), which occur naturally in the stratosphere. They are referred to collectively as odd hydrogen particles (Crutzen

*Figure 6.2* Diagrammatic representation of the sources of natural and anthropogenic ozone-destroyers

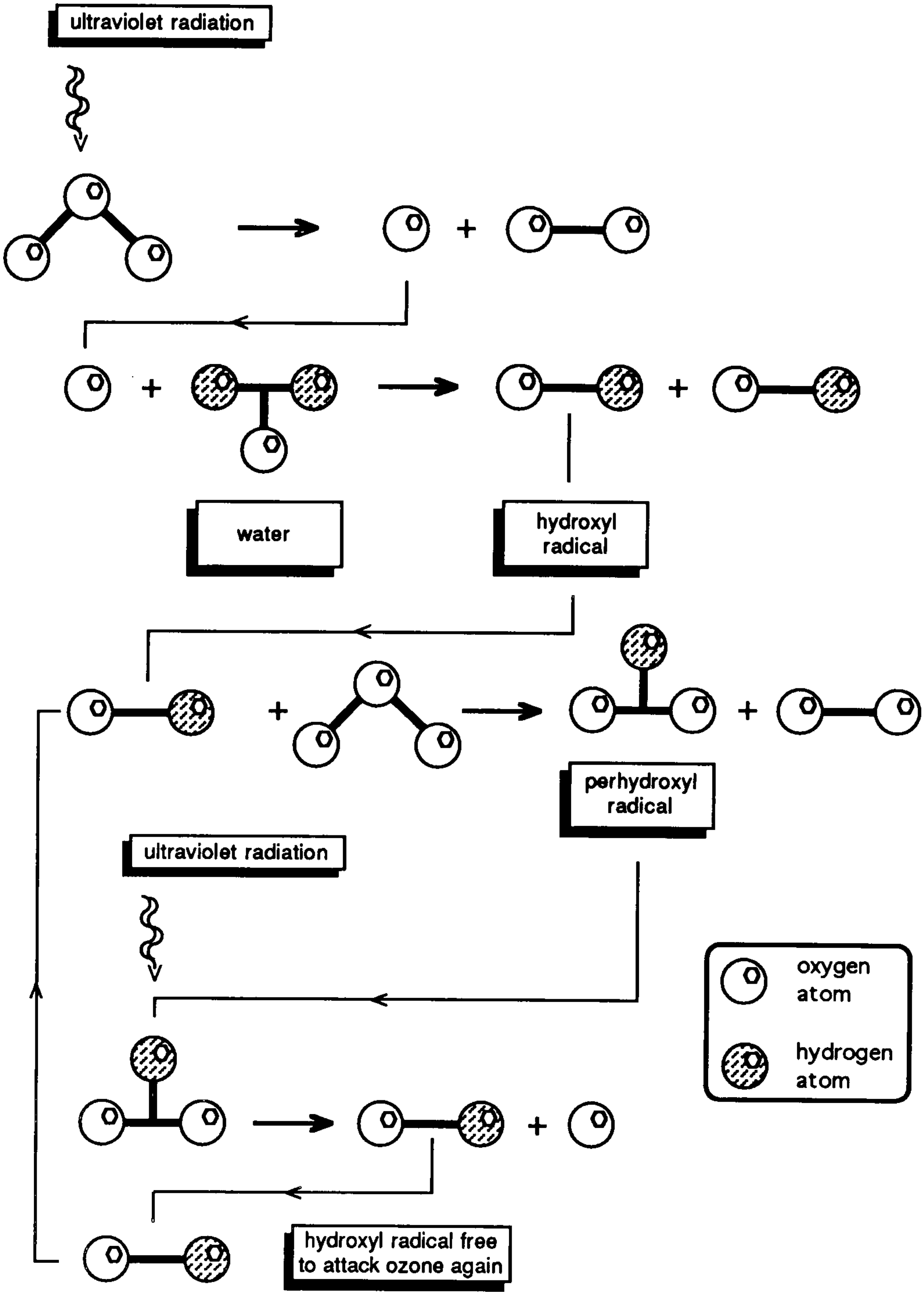



1972), and, although relatively low in total volume, they affect ozone strongly, particularly above 40km. Hammond and Maugh (1974) have estimated that the $HO_X$ group, through its catalytic properties, is responsible for about 11 per cent of the natural destruction of ozone in the stratosphere (see Figure 6.3). The odd hydrogens lose their catalytic capabilities when they are converted to water vapour.

## Nitrogen oxides

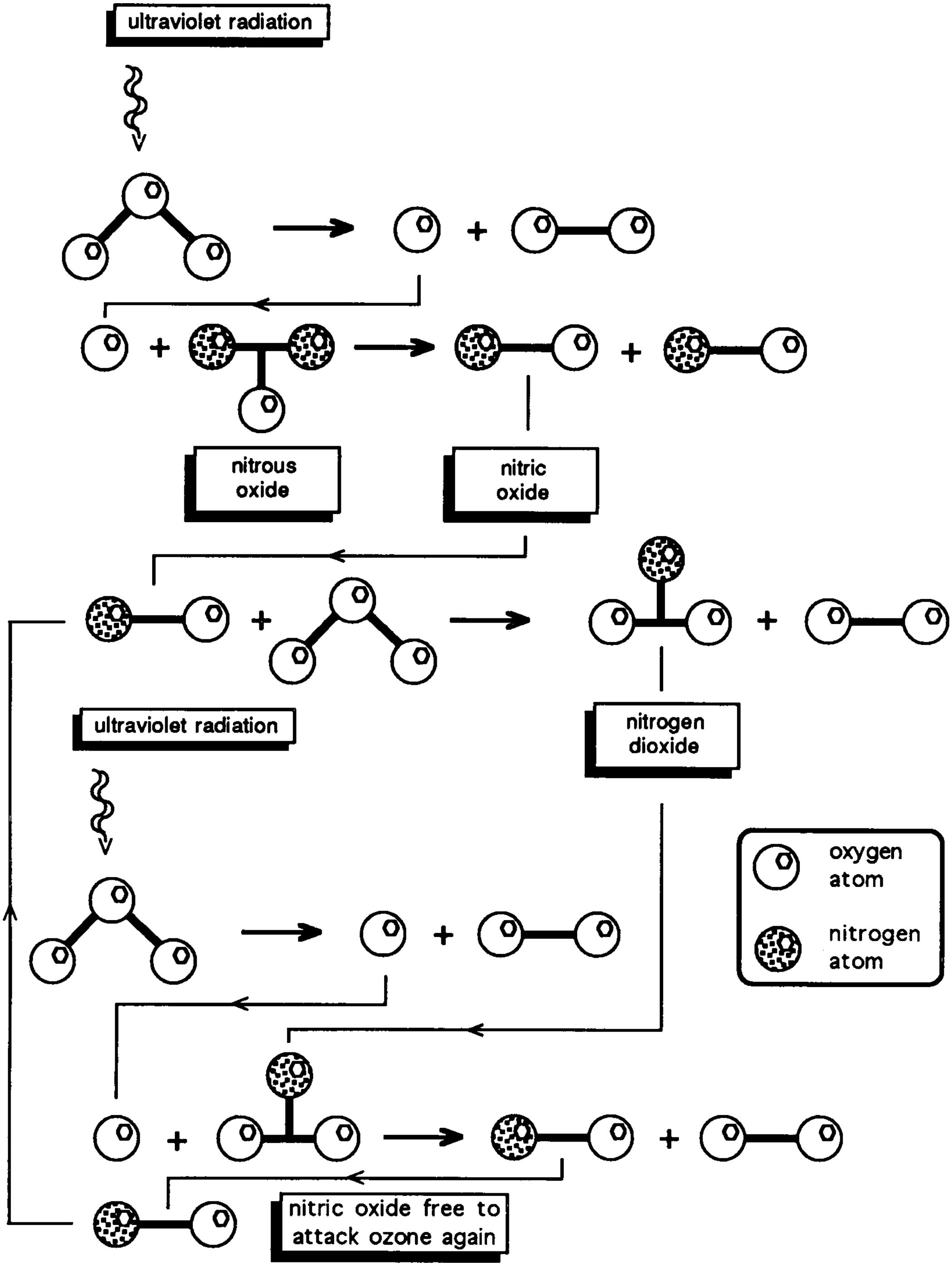
Nitrogen oxides ($NO_x$) are very effective destroyers of ozone (see Figure 6.4). Nitric oxide (NO) is most important, being responsible for 50–70 per cent of the natural destruction of stratospheric ozone (Hammond and Maugh 1974). It is produced in the stratosphere by the oxidation of nitrous oxide ($N_2O$), which has been formed at the earth's surface by the action of denitrifying bacteria on nitrites and nitrates. It may also be produced in smaller quantities by the action of cosmic rays on atmospheric gases (Hammond and Maugh 1974). Major cosmic ray activity in the past, associated with supernovas, possibly produced sufficient $NO_x$ to cause a 90 per cent reduction in the ozone concentration for periods of as much as a century (Ruderman 1974). The catalytic chain reaction created by NO is a long one. Nitric oxide diffuses only slowly into the lower stratosphere where it is converted into nitric acid, and eventually falls out of the atmosphere in rain. In contrast to the other oxides of nitrogen, the presence of nitrogen dioxide ($NO_2$) in the lower stratosphere can be beneficial to the ozone layer. It readily combines with chlorine monoxide (ClO), one of the most efficient ozone destroyers, to produce chlorine nitrate ($ClONO_2$), a much less reactive compound, thus providing some protection for lower stratospheric ozone (Brasseur and Granier 1992).

*Figure 6.3* The destruction of ozone by $HO_x$




*Source:* Based on formulae in Crutzen (1972)

*Figure 6.4* The destruction of ozone by $NO_x$




*Source:* Based on formulae in Crutzen (1972)

### Chlorine oxides

The extent to which naturally produced chlorine monoxide (CIO) contributes to the destruction of the ozone layer is not clear. The most abundant natural chlorine compound is hydrochloric acid (HC1). Although it is present in large quantities in the lower atmosphere, HCl is highly reactive and soluble in water, and Crutzen (1974) considered that it was unlikely to diffuse into the stratosphere in sufficient quantity to have a major effect on the ozone layer. The addition of large amounts of chlorine compounds to the stratosphere during volcanic eruptions was also proposed as a mechanism for the natural destruction of the ozone layer (Stolarski and Cicerone 1974), but observations of the impact of large volcanic eruptions—such as that of Mt Agung (see Chapter 5)—on the ozone layer, do not support that proposition (Crutzen 1974). The impact of naturally occurring CIO on the ozone layer was therefore considered relatively insignificant compared to that of $NO_x$ and $HO_x$. By 1977, however, measurements showed that the contribution of chlorine to ozone destruction was growing (Dotto and Schiff 1978), but largely from human rather than natural sources. Anthropogenically produced chlorine now poses a major threat to the ozone layer.

## THE HUMAN IMPACT ON THE OZONE LAYER

It had become clear by the mid-1970s that human activities had the potential to bring about sufficient degradation of the ozone layer that it might never recover. The threat was seen to come from four main sources, associated with modern technological developments in warfare, aviation, life-style and agriculture (see Figure 6.2), and involving a variety of complex chemical compounds, both old and new.

### Nuclear war and the ozone layer

When a modern thermonuclear device is exploded in the atmosphere, so much energy is released, so rapidly, that the normally inert atmospheric nitrogen combines with oxygen to produce quantities of oxides of nitrogen ($NO_x$). The rapid heating of the air also sets up strong convection currents which carry the gases and other debris into the stratosphere, and it is there that most of the $NO_x$ is deposited. Since natural $NO_x$ is known to destroy ozone, it is only to be expected that the anthropogenically produced variety would have the same effect, and one of the many results of nuclear war might be the large scale destruction of the ozone layer. Most of the studies which originally investigated the effects of nuclear explosions on the atmosphere used data generated during the nuclear bomb tests of the 1950s and 1960s. After 1963, when a moratorium on atmospheric tests of nuclear devices was declared, information from these sources was no longer available, and recent investigations have been based on statistical models.

The results of the studies of the effects of nuclear-weapon tests on the ozone layer were not conclusive. The analysis of data collected during a period of intense testing in 1961 and 1962 produced no proof that the tests had had any effect on the ozone (Foley and Ruderman 1973), although it was estimated that the explosions should have been sufficient to cause a reduction of 3 per cent in stratospheric ozone levels (Crutzen 1974). Techniques for measuring ozone levels were not particularly sophisticated in the 1960s, and, in addition, a reduction of 3 per cent is well within the normal annual fluctuation in levels of atmospheric ozone. Thus, it was not possible to confirm or refute the predicted effects of nuclear explosions on the ozone layer by analysis of the test data. Circumstantial evidence did indicate a possible link, however. Since ozone levels are known to fluctuate in phase with sunspot cycles, it was expected that peak concentrations of ozone in 1941 and 1952 would be followed by a similar peak in 1963, in accordance with the eleven-year cycle. That did not happen. Instead, the minimum level reached in 1962 increased only gradually through the remainder of the decade (Crutzen 1974). The missing sunspot cycle peak was considered to be the result of the nuclear tests, and the gradual increase in ozone in the years following was interpreted as representing the recovery from the effects of the tests, as well as the return to the normal cyclical patterns (Hammond and Maugh 1974).

Although it was not possible to establish conclusive links between nuclear explosions and ozone depletion on the basis of these individual tests, a number of theoretical studies attempted to predict the impact of a full-scale nuclear war on stratospheric ozone. Hampson (1974) estimated that even a relatively minor nuclear conflict, involving the detonation of 50 megatonnes—equivalent to 50 million tonnes of conventional TNT explosive—would lead to a reduction in global ozone levels of about 20 per cent with a recovery period of several years. He pointed out the importance of thinking beyond the direct military casualties of a nuclear conflict to those who would suffer the consequences of a major thinning of the ozone layer. Since the destruction of the ozone layer would not remain localized, the effects would be felt worldwide, not just among the combatant nations. Subsequent studies by US military authorities at the Pentagon supported Hampson's predictions. They indicated that, following a major nuclear conflict 50–70 per cent of the ozone layer might be destroyed—with the greater depletion taking place in the northern hemisphere where most of the explosions would occur (Dotto and Schiff 1978).

Similar results were obtained by Crutzen (1974) using a photochemical-diffusion model. He calculated that the amount of nitric oxide injected into the stratosphere by a 500-megatonne conflict would be more than ten times the annual volume provided by natural processes. This was considered sufficient to reduce ozone levels in the northern hemisphere by 50 per cent. Dramatic as these values may appear, they remain approximations—based on data and analyses containing many inadequacies. Interest in the impact of nuclear war on the ozone layer peaked in the mid-1970s and declined thereafter. It emerged again a decade later as part of a larger package, dealing with nuclear war and climatology, which emphasized nuclear winter (see Chapter 5).

### Supersonic transports and the ozone layer

The planning and development of a new generation of transport aircraft was well under way in North America, Europe and the USSR by the early 1970s. These were the supersonic transports (or SSTs), designed to fly higher and faster than conventional, subsonic civil airliners, and undoubtedly a major technological achievement. It became clear, however, that they could lead to serious environmental problems, if ever produced in large numbers. Initial concerns included elevated noise levels at airports and the effects of the sonic boom produced when the aircraft passed through the sound barrier, but many scientists and environmentalists saw the impact of these high-flying jets on the structure of the ozone layer as many times more serious, and more universal in its effects.

Supersonic transports received a great deal of attention between 1971 and 1974, as a result of Congressional hearings in the United States into the funding of the Boeing SST, and a subsequent Climatic Impact Assessment Program (CIAP) commissioned by the US Department of Transportation to study the effects of SSTs on the ozone layer. The findings in both cases were extremely controversial, and gave rise to a debate which continued for several years, at times highly emotional and acrimonious. It was fuelled further by a series of legal and legislative battles which ended only in 1977, when the US Supreme Court granted permission for the Anglo-French Concorde to land at New York. The proceedings and findings of the Congressional hearings and the CIAP, plus the debate that followed, have been summarized and evaluated by Schneider and Mesirow (1976) and Dotto and Schiff (1978). The arguments for and against the SSTs were as much political and economic as they were scientific or environmental. They did reveal, however, a society with the advanced technology necessary to build an SST, yet possessing a remarkably incomplete understanding of the environment into which the aircraft was to be introduced.

Like all aircraft, SSTs produce exhaust gases which include water vapour, carbon dioxide, carbon monoxide, oxides of nitrogen and some unburned hydrocarbons. These are injected directly into the ozone layer since SSTs commonly cruise at about 20 km above the surface—just below the zone of maximum stratospheric ozone concentration. Much of the initial concern over the effect of SSTs on ozone centred on the impact of water vapour, which was considered capable of reducing ozone levels through the creation of the hydroxyl radical, a known ozone-destroying catalyst. Later observations, which indicated that a 35 per cent increase in water vapour had been accompanied by a 10 per cent increase in ozone, rather than the expected decrease (Crutzen 1972), caused the role of water vapour to be re-evaluated. It was suggested that water vapour helped to preserve the ozone layer through its interaction with other potential catalysts. It converted $NO_x$ to nitric acid, for example, and therefore nullified its ozone-destroying properties (Crutzen 1972; Johnson 1972). By the time this had been confirmed, in 1977, $NO_x$ had already replaced $HO_x$ as the villain in SST operations (Dotto and Schiff 1978).

In 1970, Crutzen drew attention to the role of $NO_x$ in the destruction of ozone through catalytic chain reactions, and in the following year, just as the SST debate was beginning to take off, Johnston (1971) warned that $NO_x$ emitted in the exhaust gases of 500 SSTs could reduce ozone levels by as much as 22–50 per cent. Later predictions by (Crutzen 1972) suggested a 3–22 per cent reduction, while Hammond and Maugh reported in 1974 that the net effect of the $NO_x$ emissions from a fleet of 500 SSTs would be a 16 per cent reduction in ozone in the northern hemisphere and an 8 per cent reduction in the southern hemisphere.

When all of this was under consideration in the early 1970s, it was estimated that the world's fleet of SSTs would grow to several hundred aircraft by the end of the century and perhaps as many as 5,000 by the year 2025 (Dotto and Schiff 1978). The $NO_x$ emissions from such a fleet were considered capable of thinning the ozone layer sufficiently to produce an additional 20,000 to 60,000 cases of skin cancer in the United States alone (Hammond and Maugh 1974). Other predicted environmental impacts included damage to vegetation and changes in the nature and growth of some species as a result of mutation. The extent to which such threats helped to kill SST development is difficult to estimate. At the time, the environmental arguments seemed strong, but the economic conditions were not really right for development, and that, as much as anything else, led to the scrapping of the projected Boeing SST. Development of the Soviet Tupolev-144 and the Anglo-French Concorde went ahead, with the latter being the more successful of the two in terms of production numbers and commercial route development. Less than 10 SSTs are currently in operation, and the effects on the ozone layer are generally considered to be negligible.

## Chlorofluorocarbons, halons and the ozone layer

If there was some doubt about the impact of SST exhaust emissions on the ozone layer, the effects of some other chemicals seemed less uncertain. Among these, the chlorofluorocarbon (CFC) group and related bromofluorocarbons or halons have been identified as potentially the most dangerous (see Table 6.2). The CFCs, sometimes referred to by their trade name, *Freon,* came to prominence as a result of lifestyle changes which have occurred since the 1930s. They are used in refrigeration and air conditioning units, but, until recently, their major use was as propellants in aerosol spray cans containing deodorants, hair spray, paint, insect repellant and a host of other substances. When the energy crisis broke, they were much in demand as foaming agents in the production of polyurethane and polystyrene

*Table* 6.2 Some common anthropogenically produced ozone destroying chemicals

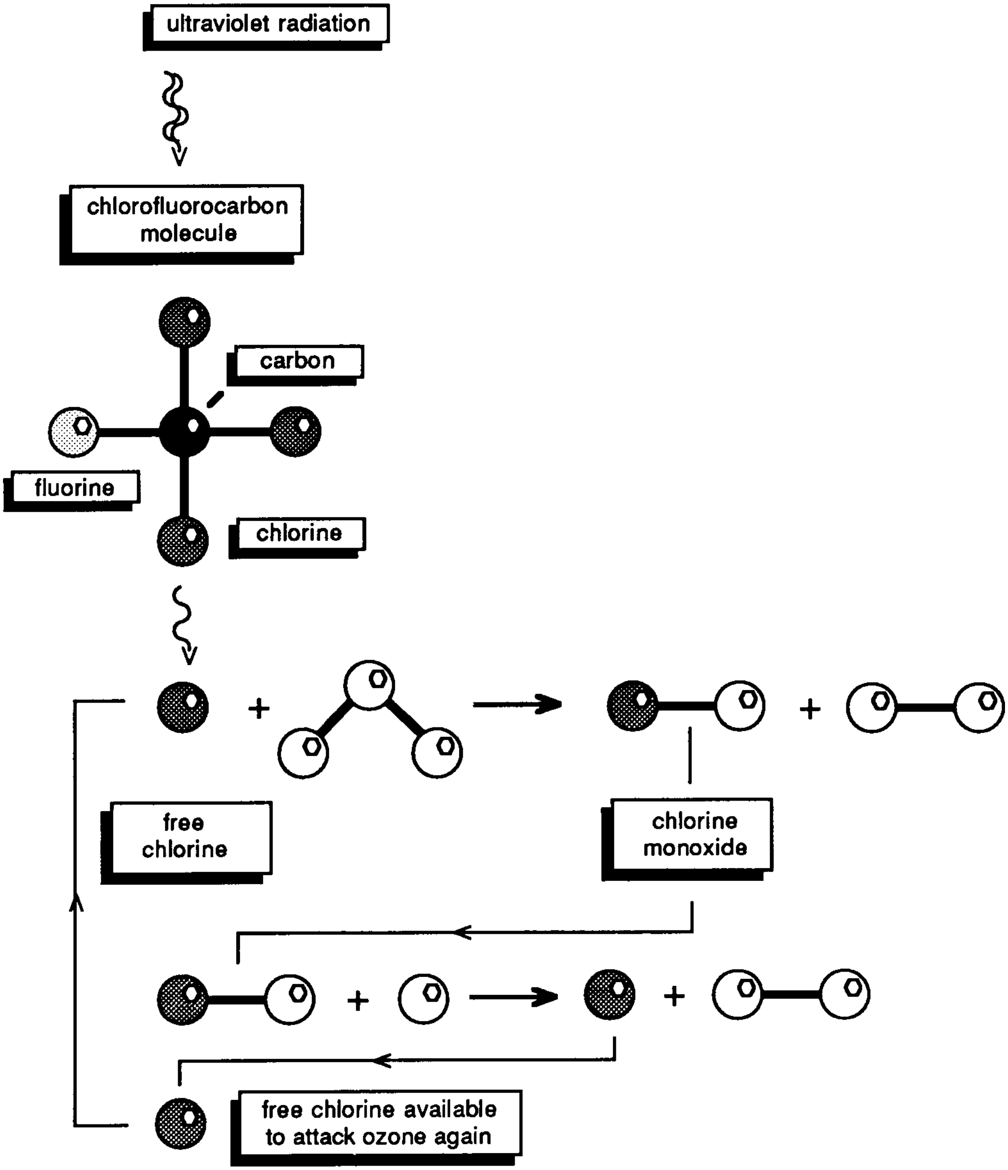
| *Chemical compound* | *Ozone depleting potential (ODP)** | *Current or former use* | *Phase-out date* | *Replacement* | *Replacement advantage (A) or disadvantage (D)* |
|---|---|---|---|---|---|
| CFC-11 | 1.0 | Foaming agent for rigid foams (insulation: food packaging) and flexible foams | 1996 | HCFC-22<br>HCFC-123<br>HCFC-141b<br>HFC-134a | (A) ODP = 0.05<br>(A) ODP = 0.02<br>(D) flammable<br>(A) ODP = 0.0 |
| CFC-12 | 1.0 | Refrigeration: air conditioning | 1996 | Propane/butane ammonia | (D) explosive |
| CFC-113 | 0.8 | Solvent | 1996 | HCFC-132b<br>terpene solvent<br>water | (D) toxic<br>(D) flammable<br>(A) cheap and safe, but<br>(D) limited utility |
| CFC-115 | 0.6 | Refrigeration: air conditioning | 1996 | HCFC-22<br>HCFC-123<br>HFC-134a | (A) ODP = 0.05<br>(A) ODP = 0.02<br>(A) ODP = 0.0 |
| Halon 1211 | 3.0 | Portable fire extinguishers | 1994 | intergen (nitrogen/argon/ $CO_2$) mix | (A) inexpensive |
| Halon 1301 | 10.0 | Total flooding fire control systems | 1994 | Intergen (nitrogen/argon/ $CO_2$) mix | (A) inexpensive |
| Methyl chloroform | 0.1 | Solvent | 1996 | ? | ? |
| Carbon tetrachloride | 1.1 | Solvent | 1996 | ? | ? |
| Methyl bromide | 60.0 | Fumigant/pest control | ? | ? | ? |

*Source:* Compiled from data in Environment Canada (1989), MacKenzie (1992), Tickell (1992)
* ODP is a measure of the capacity of a chemical to destroy ozone, with the ODP of CFC-1 1 and CFC-1 2 as a base of 1 .0

foam used to improve home insulation. Polymer foams are also included in furniture and car seats, and, with the growth of the convenience food industry, they were used increasingly in the manufacture of fast food containers and coffee cups. The gases are released into the atmosphere from leaking refrigeration or air conditioning systems, or sprayed directly from aerosol cans. They also escape during the manufacture of the polymer foams, and are gradually released as the foams age. Halons are widely used in fire extinguishers and fire protection systems for computer centres, industrial control rooms and aircraft. Although they are less abundant in the atmosphere than CFCs, their ability to cause ozone depletion may be 3–10 times greater (Environment Canada 1989).

Advantages of CFCs and halons for such purposes include their stability and low toxicity; under normal conditions of temperature and pressure they are inert—that is, they do not combine readily with other chemicals nor are they

*Figure 6.5* The break-down of a chlorofluorocarbon molecule ($CFCl_3$) and its effect on ozone




easily soluble in water. In consequence, they remain in the environment relatively unchanged. Over the years, they have gradually accumulated, and diffused into the upper atmosphere. Once they reach the upper atmosphere, however, they encounter conditions under which they are no longer inert—conditions which cause them to break down and release by-products which are immensely destructive to the ozone layer (see Figure 6.5).

In 1974, two scientists working in the United States on the photochemistry of the stratosphere, came to the conclusion that CFCs, however inert they may be at the earth's surface, are highly susceptible to break down by the ultraviolet radiation present in the upper atmosphere.

Molina and Rowland (1974) recognized that the photochemical degradation of CFCs releases chlorine, which, through catalytic action, has a remarkable ability to destroy ozone. The importance of the chlorine catalytic chain lies in its efficiency; it is six times more efficient catalytically than the NO cycle. The chain is only broken when the Cl or ClO gains a hydrogen atom from the odd hydrogen group, or from a hydrocarbon such as methane ($CH_4$), and is converted into HCl, which diffuses into the lower atmosphere, eventually to be washed out by rain (Hammond and Maugh 1974). Similar conclusions were reached independently at about the same time by other researchers (Crutzen 1974; Cicerone *et al.* 1974; Wofsy *et al.* 1975), and, with the knowledge that the use of CFCs had been growing since the late 1950s, the stage seemed set for an increasingly rapid thinning of the earth's ozone shield, followed by a rise in the level of ultraviolet radiation reaching the earth's surface.

The world production of CFCs reached 700,000 tonnes in 1973 (Crutzen 1974), after growing at an average rate of about 9 per cent in the 1960s (Molina and Rowland 1974). The total production of CFCs and halons amounted to 1,260,000 tonnes in 1986, before falling to 870,000 tonnes in 1990 (Environment Canada 1992). The effects of such increases in production were exacerbated by the stability of the products, which allowed them to remain in the atmosphere for periods of 40 to 150 years, and measurements in the troposphere in the early 1970s indicated that almost all of the CFCs produced in the previous two decades were still there (Molina and Rowland 1974). This persistence means that, even after a complete ban on the production of CFCs, the effects on the ozone layer might continue to be felt for a further 20 to 30 years and, under certain circumstances, for as long as 200 years after production ceased (Crutzen 1974; Wofsy *et al.* 1975).

The predicted effects of all of this on the ozone layer varied. Molina and Rowland (1974) estimated that the destruction of ozone by chlorine was already equivalent to that produced by naturally occurring catalysts. Crutzen (1974) predicted that a doubling of CFC production would cause a corresponding 10 per cent reduction in ozone levels, whereas Wofsy *et al.* (1975) estimated that, with a growth rate of 10 per cent per year, CFCs could bring about a 20 per cent reduction by the end of the century. All indicated the preliminary nature of their estimates and the inadequacy of the existing knowledge of the photochemistry of the stratosphere, but such cautions were ignored as the topic took on a momentum of its own, and the dire predictions made following the SST studies were repeated. The spectre of thousands of cases of skin cancer linked to a seemingly innocuous product like hairspray or deodorant was sufficiently different that it excited the media and, through them, the general public. Although CFCs were being employed as refrigerants and used in the production of insulation, the problem was usually presented as one in which the convenience of aerosol spray products was being bought at the expense of the global environment. In 1975 there was some justification for this, since, at that time, 72 per cent of CFCs were used as propellants in aerosol spray cans (Webster 1988), and the campaign against that product grew rapidly.

The multi-million dollar aerosol industry led by major CFC producers such as DuPont reacted strongly. Through advertising and participation in US government hearings, they emphasized the speculative nature of the Molina-Rowland hypothesis, and the lack of hard scientific facts to support it. The level of concern was high, however, and the anti-aerosol forces met with considerable success. Eventually manufacturers were forced to replace CFCs with less hazardous propellants (Dotto and Schiff 1978). A partial ban on CFCs, covering their use in hair and deodorant sprays was introduced in the United States in 1978 and in Canada in 1980. CFC aerosol spray use remained high in Europe where there was no ban. In 1989, however, the European Community agreed to eliminate the production and use of CFCs by the end of the century.

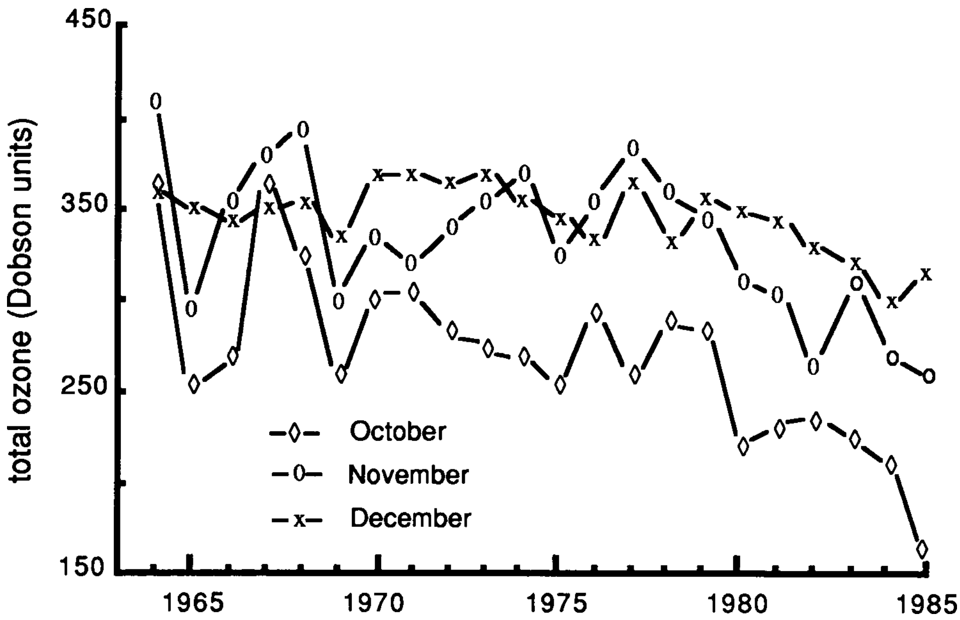
The CFC controversy had ceased to make headlines by the late 1970s, and the level of public concern had fallen away. Monitoring of the ozone layer showed little change. Ozone levels were not increasing despite the ban on aerosol sprays, which was only to be expected given the slow rate of decay of the existing CFCs, but the situation did not seem to be worsening. Quite unexpectedly, in 1985, scientists working in the Antarctic announced that they had discovered a 'hole' in the ozone layer, and all of the fears suddenly returned.

## The Antarctic ozone hole

Total ozone levels have been measured at the Halley Bay base of the British Antarctic Survey for more than thirty years beginning in the late 1950s. Seasonal fluctuations were observed for most of that time, and included a thinning of the ozone above the Antarctic during the southern spring, which was considered part of the normal variability of the atmosphere (Schoeberl and Krueger 1986). This regular minimum in the total ozone level began to intensify in the early 1980s, however (see Figure 6.6). Farman *et al.* (1985) reported that it commonly became evident in late August, and got progressively worse until, by mid-October, as much as 40 per cent of the ozone layer above the Antarctic had been destroyed. Usually the hole would fill by November, but during the 1980s it began to persist into December. The intensity of the thinning and its geographical extent were originally established by ground based measurements, and later confirmed by remote sensing from the Nimbus-7 polar orbiting satellite (Stolarski *et al.* 1986).

As was only to be expected after the aerosolspray-can experience in the 1970s, the immediate response was to implicate CFCs.

*Figure 6.6* Changing ozone levels at the South Pole (1964–85) for the months of October, November and December




*Source:* After Komhyr *et al.* 1986
*Note:* Dobson units (DU) are used to represent the thickness of the ozone layer at standard (sea-level) temperature and pressure (1 DU is equivalent to 0.01 mm)

Measurements of CFCs at the South Pole indicating a continuous increase of 5 per cent per year tended to support this, although the original fluctuation had been present before CFCs were released into the atmosphere in any quantity (Schoeberl and Krueger 1986). Other researchers suggested that gases such as $NO_x$ (Callis and Natarajan 1986) and the oxides of chlorine ($ClO_x$) and bromine ($BrO_x$) (Crutzen and Arnold 1986) were the culprits. As the investigation of the Antarctic ozone layer intensified, it became clear that the chemistry of the polar stratosphere is particularly complex. Although the stratosphere is very dry, it becomes saturated at the very low temperatures reached during the winter months, and clouds form. Nitric and hydrochloric acid particles in these polar stratospheric clouds enter into a complex series of reactions—involving, for example, denitrification and dehydration—which ultimately lead to the release of chlorine. In the form of ClO it then attacks the ozone (Shine 1988). The evaporation of the polar stratospheric clouds in the spring, as temperatures rise, brings an end to the reactions, and allows the recovery of the ozone layer.

The chemical reactions which lead to the destruction of the ozone following the formation of polar stratospheric clouds, take place initially on the surface of ice particles in the clouds. Similar heterogeneous chemical reactions on the surface of sulphate aerosol particles have also been identified as contributing to major thinning of the Antarctic ozone layer (Brasseur and Granier 1992; Deshler *et al.* 1992; Keys *et al.* 1993). The injection of large volumes of sulphate into the lower stratosphere during the eruptions of Mount Pinatubo and Mount Hudson in 1991 was followed by rapid destruction of the ozone layer at altitudes of 9–13 km. During September 1991 alone, almost 50 per cent of the ozone in the lower stratosphere was destroyed (Deshler *et al.* 1992). The role of the sulphate aerosol was confirmed by modelling chemical, radiative and dynamical processes in the stratosphere (Braseur and Granier 1992), by direct measurement of the levels of volcanic aerosol and ozone depletion (Deshler *et al.* 1992), and by the presence of chemicals normally associated with heterogeneous chemical reactions at a time when stratospheric temperatures remained too high for polar stratospheric clouds to form. The background sulphate aerosols in the stratosphere provided an alternative surface upon which the reactions took place (Keys *et al.* 1993).

Following the initial identification of the sulphate/ozone relationship in the Antarctic in late 1991, additional evidence was obtained from Thule in Greenland. Measurements taken in the first three months of 1992 showed a negative correlation between aerosol counts and ozone levels in the middle stratosphere, with fluctuations of as much as 50 per cent in ozone content (di Sarra *et al.* 1992). One year later over Canada, record low ozone values were measured at altitudes at which aerosols from the Mount Pinatubo eruption had been observed (*Kerr et al.* 1993).

When the aerosols from Pinatubo and Hudson initially spread into the Antarctic in 1991, they were unable to penetrate beyond an altitude of 14–15 km because of the presence of the circumpolar vortex. As a result, the thinning of the ozone layer in the upper stratosphere remained close to normal levels. By late 1992, however, the aerosols had spread evenly over the polar region. Record low levels of ozone were reported over the pole and over southern Argentina and Chile, while the thinning of the ozone layer also reached record levels over the northern hemisphere (Gribbin 1992), and global ozone levels were more than 4 per cent below normal (Kiernan 1993).

In contrast to these approaches which emphasize the chemistry of the stratosphere, there are the so-called dynamic hypotheses, which seek to explain the variations in ozone levels in terms of circulation patterns in the atmosphere. Certain observations do support this. For example, at the time the ozone level in the hole is at its lowest, a ring of higher concentration develops around the hole at between 40 and 50°S. The hole begins to fill again in November, seemingly at the expense of the zone of higher concentration (Stolarski *et* *al.* 1986). Bowman (1986) has suggested that the main mechanism involved is the circumpolar vortex. The Antarctic circumpolar vortex is a particularly tight, self-contained wind system, which is most intense during the southern winter, when it permits little exchange of energy or matter across its boundaries. Thus it prevents any inflow of ozone from lower latitudes, where most of it is produced, allowing the cumulative effects of the catalytic, ozone-destroying chemicals to become much more obvious. The breakdown of the vortex allows the transfer of ozone from lower latitudes to fill the hole. Observations show that when the breakdown of the vortex is late, ozone levels become very low, and when the breakdown is early, the ozone hole is less well-marked. The possibility also exists that the cooling of the atmosphere above the Antarctic, resulting from ozone depletion, will encourage the vortex to persist longer, become more intense and perhaps even spread to lower latitudes, thus compounding the problem (Gribbin 1993).

Most authorities tend to place the hypotheses, which attempt to explain the Antarctic ozone levels, into either chemical or dynamic categories (Rosenthal and Wilson 1987), but there are several hypotheses which might be placed in a third group, combining both chemical and dynamic elements. The paper which first drew attention to the increased thinning of the Antarctic ozone layer, for example, might be classed in the chemical group since it attributes the decline to CFCs (Farman *et al.* 1985). It does, however, have a dynamic element in its consideration of the polar vortex, which appears to be a necessary prerequisite for the ozone depletion.

Another hypothesis which combines dynamic and chemical elements is that proposed by Callis and Natarajan (1986). They suggest that the depletion of the ozone in the Antarctic is a natural phenomenon, caused by elevated levels of $NO_x$ in the atmosphere during periods of increased solar activity. Sunspot activity did peak at a particularly high level in 1979, and continued into the early 1980s, but measurements by Dr Susan Solomon, released at a special meeting of the Royal Meteorological Society in 1988, indicated that $NO_x$ levels in the lower stratosphere in the Antarctic were too low to have the necessary catalytic effect (Shine 1988).

Comparison of the situation in Antarctica with that in the Arctic provides indirect support for the role of the circumpolar vortex in the thinning of the ozone layer. The circumpolar vortex in the northern hemisphere is much less intense than its southern counterpart, which may explain, in part at least, the absence of a comparable hole in the ozone over the Arctic (Farman *et al.* 1985). A smaller, more mobile hole was identified in the ozone above the Arctic in the late 1980s, however, and further investigation set in motion (Shine 1988).

The European Arctic Stratospheric Ozone Experiment (EASOE)—involving scientists from the European Community, the United States, Canada, Japan, New Zealand and Russia—was undertaken during the northern winter of 1991–92, using ground measurements, balloons, aircraft and a variety of modelling techniques to establish the nature and extent of ozone depletion over the Arctic (Pyle 1991). Preliminary results tended to confirm the absence of a distinct hole over the Arctic, but noted the higher than average ozone loss in middle latitudes. Because the Arctic stratosphere is generally warmer than its southern counterpart, polar stratospheric clouds are less ready to form, and ozone destruction is less efficient. The less developed Arctic circumpolar vortex also allows the loss of ozone at the pole to be offset to some extent by the influx of ozone from more southerly latitudes. The relatively free flow of air out of the Arctic in the winter might also contribute the peculiar patterns of ozone depletion in the north. Chemicals incapable of destroying ozone because of the lack of energy available during the Arctic winter night become energized when carried south into the sunlight of mid-latitudes, and cause greater thinning there than at the pole (Pyle 1991). By March 1992, the EASOE had detected decreases of 10–20 per cent in Arctic ozone (Concar 1992). Although this was less than the 40 per cent reduction initially predicted, by the middle of the year the Canadian Atmospheric Environment Service had become so concerned about the destruction of ozone in mid-latitudes that it began to include ultraviolet radiation warnings along with its regular weather forecasts, and in March 1993 it announced that the ozone layer above Toronto and Edmonton—at 43°N and 53°N respectively—was thinner than at any time since records began (Environment Canada 1993).

There is as yet no one theory which can explain adequately the creation of the Antarctic ozone hole or the thinning of the ozone layer in the northern hemisphere. The impact of CFCs is considered the most likely cause by many, however. There can be little doubt that the link between the ozone hole and the CFCs, tenuous as it may have seemed to some scientists, helped to revive environmental concerns and contributed to the speed with which the world's major industrial nations agreed in Montreal in 1987, to take steps to protect the ozone layer.

### Agricultural fertilizers, nitrous oxide and the ozone layer

When concern for the ozone layer was at its height, compounds other than CFCs were identified as potentially harmful. These included nitrous oxide, carbon tetrachloride and methyl chloroform. Methyl bromide has recently been added to the group. It is used extensively as a fumigant to kill pests in the fruit and vegetable industry, and may be responsible for as much as 10 per cent of existing ozone depletion. However, its actual impact is still a matter of dispute (MacKenzie 1992). Nitrous oxide ($N_2O$), as one of the oxides of nitrogen group, known for their ability to destroy ozone, has received most attention. It is produced naturally in the environment by denitrifying bacteria which cause it to be released from the nitrites and nitrates in the soil. It is an inert gas, not easily removed from the troposphere. Over time, it gradually diffuses into the stratosphere where the higher energy levels cause it to be oxidized into NO, leading to the destruction of ozone molecules. This process was part of the earth/ atmosphere system before human beings came on the scene, and with no outside interference, natural ozone levels adjust to the output of $N_2O$ from the soil and the oceans.

One of society's greatest successes has been the propogation of the human species, as a glance at world population growth will show. This has occurred for a number of reasons, but would not have been possible without a growing ability to supply more and more food as population numbers grew. By the late 1940s and 1950s, this ability was being challenged as population began to outstrip food supply. In an attempt to deal with the problem, new agricultural techniques were introduced into Third World countries, where the need was greatest. A central element in the process was the increased use of nitrogen fertilizers along with genetically improved grains, which together produced the necessary increase in agricultural productivity. Since that time, continued population growth has been paralleled by the growth in the use of nitrogen-based fertilizers (Dotto and Schiff 1978).

The nitrogen in the fertilizer used by the plants eventually works its way through the nitrogen cycle, and is released into the air as $N_2O$ to initiate the sequence which ultimately ends in the destruction of ozone. Thus, in theory, the pursuit of greater agricultural productivity through the increased application of nitrogen fertilizers is a threat to the ozone layer. There is, however, no proof that increased fertilizer use has, or ever will, damage the ozone layer, through the production of $N_2O$. If proof does emerge, it will create a situation not uncommon in humankind's relationship with the environment, in which a development designed to combat one problem leads to others, unforeseen and perhaps undiscovered until major damage is done. As Schneider and Mesirow (1976) point out, the dilemma lies in the fact that nitrogen fertilizers are absolutely essential to feed a growing world population and improve its quality of life, yet success might lead to a thinning of the ozone layer with consequent climatic change and biological damage from increased ultraviolet radiation. If monitoring does reveal that $N_2O$ emissions are increasing, some extremely difficult judgements will have to be made; judgements which could have a far greater impact than the grounding of SSTs or the banning of CFCs from use in aerosol spray cans.

## THE BIOLOGICAL AND CLIMATOLOGICAL EFFECTS OF CHANGING OZONE LEVELS

Declining concentrations of stratospheric ozone allow more ultraviolet radiation to reach the earth's surface. Even after a decade and a half of research, the impact of that increase is still very much a matter of speculation, but most of the effects which have been identified can be classified as either biological or climatological.

### Biological effects.

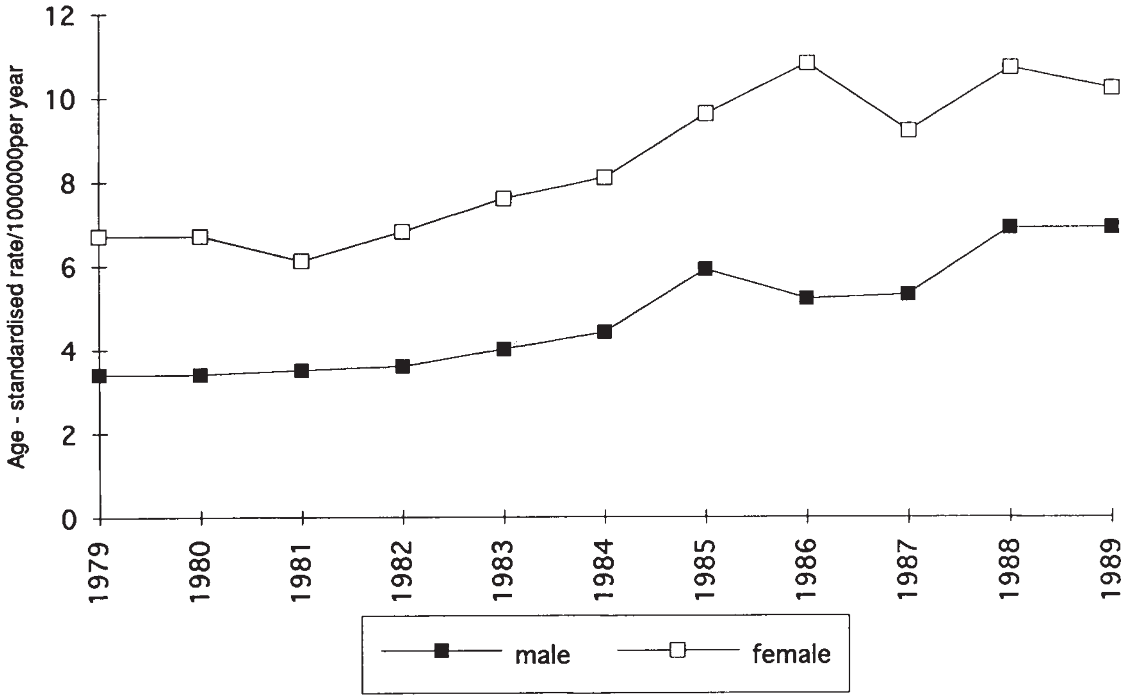
In moderate amounts ultraviolet radiation has beneficial effects for life on earth. It is a powerful germicide, for example, and triggers the production of Vitamin D in the skin. Vitamin D allows the body to fix the calcium necessary for proper bone development; lack of it may cause rickets, particularly in growing children. High intensities of ultraviolet radiation, however, are harmful to all forms of life.

Lifeforms have evolved in such a way that they can cope with existing levels of ultraviolet radiation. They are also quite capable of surviving the increases in radiation caused by short-term fluctuations in ozone levels. Most organisms would be unable to cope with the cumulative effects of progressive thinning of the ozone layer, however, and the biological consequences would be far-reaching.

The most serious concern is over rising levels of UV-B—the radiation recognized as causing most biological damage. Intense UV-B rays alter the basic foundations of life, such as the DNA molecule and various proteins (Crutzen 1974). They also inhibit photosynthesis. Growth rates in plants such as tomatoes, lettuce and peas are reduced, and experimental exposure of some plants to increased ultraviolet radiation has produced an increased incidence of mutation (Hammond and Maugh 1974). Insects, which can see in the ultraviolet sector of the spectrum, would have their activities disrupted by increased levels of ultraviolet radiation (Crutzen 1974).

Most of the concern for the biological effects of declining ozone levels has been focused on the impact of increased ultraviolet radiation on the human species. The potential effects include the increased incidence of sunburn, premature ageing of the skin among white populations and greater frequency of allergic reactions caused by the effects of ultraviolet light on chemicals in contact with the skin (Hammond and Maugh 1974). These are relatively minor, however, in comparison to the more serious problems of skin cancer and radiation blindness, both of which would become more frequent with higher levels of ultraviolet radiation. Skin cancer had a prominent role in the SST and CFC debates of the 1970s (Dotto and Schiff 1978), and it continues to evoke a high level of concern. The number of additional skin cancers to be expected as the ozone layer thins is still a matter of debate, but a commonly accepted estimate is that a 1 per cent reduction in ozone allows an increase in UV-B of 1–2 per cent. This in turn leads to a 2–4 per cent increase in the incidence of non-melanoma skin cancers (Concar 1992). Hammond and Maugh (1974) have suggested that a 5 per cent reduction in ozone levels would cause an additional 20,000 to 60,000 skin cancers in the United States alone. The US National Academy of Sciences has also estimated that a 1 per cent decline in ozone would cause 10,000 more cases of skin cancer per year (Lemonick 1987). Many skin cancers are non-malignant and curable, but only after painful and sometimes disfiguring treatment. A relatively small proportion—the melanomas—are

*Figure 6.7* Incidence of melanoma in Scotland, 1979–89




*Source:* From Mackie *et al.* 1992

malignant and usually fatal (Dotto and Schiff 1978). The US Environmental Protection Agency (EPA) forecasts that 39 million more people than normal could contract skin cancer within the next century, leading to more than 800,000 additional deaths (Chase 1988).

Levels of skin cancer are currently rising among the white-skinned peoples of the world, but there is no direct evidence that the rise is linked to thinning ozone. Rather, it may be caused by lifestyle factors, such as the popularity of seaside holidays in sunny locations and fashion trends which encourage a 'healthy' tan. In Scotland, between 1979 and 1989, there was an 82 per cent increase in the occurrence of melanomas (Mackie *et al.* 1992) (see Figure 6.7), and similar values apply across most of northern Europe, an area not renowned for abundant sunshine and not particularly affected by thinning ozone until relatively recently. Rising skin cancer totals there may reflect the impact of exposure to higher levels of ultraviolet radiation on the beaches of southern Europe, which have become popular vacation spots for northerners. Since there is a time lag between exposure and the discovery of cancer, current increases may represent the results of cell damage initiated 10–20 years ago. It also follows that, despite increasing attempts by health authorities to reduce public exposure to the sun, the rising level of skin cancers is likely to continue for some time to come.

The situation is particularly serious in Australia, where skin cancer is ten times more prevalent than in northern Europe (Concar 1992). Average summer receipts of UV-B have increased by 8 per cent since 1980 in southern Australia, and in New Zealand, the amount of ultraviolet radiation reaching the earth's surface is double that in Germany (Seckmeyer and

McKenzie 1992). Since the Antarctic ozone hole extends over the southern continents at the end of spring, the higher levels of ultraviolet radiation are probably associated with the thinner ozone at that time. However, that in itself is considered insufficient to explain the high rates of skin cancer. Epidemiologists continue to place most of the blame on social factors which encourage over-exposure to ultraviolet light, rather than on ozone thinning. The consensus among researchers is that the latter will only begin to contribute to skin cancer statistics in the second half of the 1990s (Concar 1992). To counter this, both the Australian and New Zealand governments have initiated campaigns to discourage exposure to the sun, by advocating the use of sunscreen lotions and wide-brimmed hats and by promoting a variety of behavioural changes that would keep people out of the sun during the high risk period around solar noon (Concar 1992; Seckmeyer and McKenzie 1992). A similar approach is being developed in Canada, but in the northern hemisphere concern over the dangers of excess ultraviolet radiation generally lags behind that in the south.

The attention paid to skin cancer has caused other effects to be overshadowed. Radiation, blindness and cataracts were early identified as potential problems (Dotto and Schiff 1978). More recently, damage to the human immune system has been postulated, and there is some evidence that ultraviolet light may be capable of activating the AIDS virus (Valerie *et al.* 1988).

Concentration on the direct effects of ozone

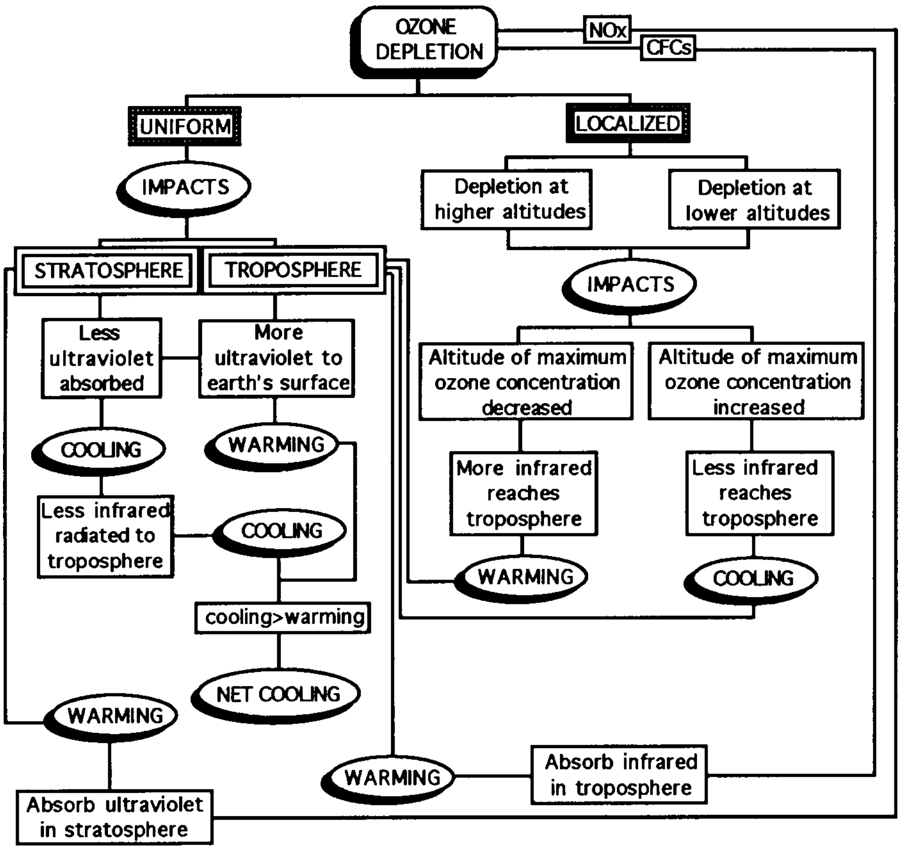



*Figure 6.8* Schematic representation of the radiation and temperature changes accompanying the depletion of stratosphere ozone

depletion on people is not surprising or unexpected. Much more research into other biological effects is required, however. Human beings are an integral part of the earth/atmosphere system and, as Dotto and Schiff (1978) suggest, humankind may experience the consequences of ozone depletion through its effects on plants, animals and climate. The impact would be less direct, but perhaps no less deadly.

## Climatological effects

The climatological importance of the ozone layer lies in its contribution to the earth's energy budget (see Figure 6.8). It has a direct influence on the temperature of the stratosphere through its ability to absorb incoming radiation. Indirectly, this also has an impact on the troposphere. The absorption of short-wave radiation in the stratosphere reduces the amount reaching the lower atmosphere, but the effect of this is limited to some extent by the emission of part of the absorbed short-wave energy into the troposphere as infrared radiation.

Natural variations in ozone levels alter the amounts of energy absorbed and emitted, but these changes are an integral part of the earth/atmosphere system, and do little to alter its overall balance. In contrast, chemically induced ozone depletion could lead to progressive disruption of the energy balance, and ultimately cause climatic change. The total impact would depend upon a number of variables, including the amount by which the ozone concentration is reduced, and the altitude at which the greatest depletion occurred (Schneider and Mesirow 1976).

A net decrease in the amount of stratospheric ozone would reduce the amount of ultraviolet absorbed in the upper atmosphere, producing cooling in the stratosphere. The radiation no longer absorbed would continue on to the earth's surface, causing the temperature there to rise. This simple response to declining ozone concentration is complicated by the effects of stratospheric cooling on the system. The lower temperature of the stratosphere would cause less infrared radiation to be emitted to the troposphere, and the temperature of the lower atmosphere would also fall. Since the cooling effect of the reduction in infrared energy would be greater than the warming caused by the extra long-wave radiation, the net result would be a cooling at the earth's surface. The magnitude of the cooling is difficult to assess, but it is likely to be small. Enhalt (1980) has suggested that a 20 per cent reduction in ozone concentration would lead to a global decrease in surface temperature of only about 0.25°C.

An increase in total ozone in the stratosphere would be likely to cause a rise in surface temperatures as a result of greater ultraviolet absorption, and the consequent increase in infrared energy radiated to the surface. Since current concern is with ozone depletion, the question of rising ozone levels has received little attention. However, the possibility that natural, ozoneenhancing processes might at times be sufficiently strong to reverse the declining trend cannot be ruled out completely.

Stratospheric ozone is not evenly distributed through the upper atmosphere. Its maximum concentration is 25 km above the surface (Crutzen 1972). Destruction of ozone does not occur uniformly throughout the ozone layer, and, as a result, the altitude of maximum concentration may change. A decrease in that altitude will lead to a warming of the earth's surface, whereas an increase will have the opposite effect, and lead to cooling (Schneider and Mesirow 1976). CFCs begin to be most effective as ozone destroyers at about 25 km above the surface (Enhalt 1980). They therefore tend to push the level of maximum concentration down, and promote warming.

Thus any estimate of the impact of ozone depletion on climate must consider not only changes in total stratospheric ozone, but also changes in the altitude of its maximum concentration. The depletion of total stratospheric ozone will always tend to cause cooling, but that cooling may be enhanced by an increase in the altitude of maximum concentration or retarded by a decrease in altitude.

Just as there are variations in the vertical distribution of ozone, there are also variations in its horizontal distribution. The latter are seasonal and associated with changing wind and pressure systems in the lower stratosphere (Crutzen 1974). Most ozone is manufactured above the tropics, and is transported polewards from there. Increased levels of ozone have been identified regularly at middle and high latitudes in late winter and spring in the northern hemisphere (Crutzen 1972), and the redistribution of ozone by upper atmospheric winds has been implicated by a number of authors in the development of the Antarctic ozone hole (Shine 1988). Such changes have local and short-term effects which might reinforce or weaken the global impact of ozone depletion.

Further complications are introduced by the ability of several of the chemicals which destroy ozone to interfere directly with the energy flow in the atmosphere. Ramanathan (1975) has shown that ozone-destroying CFCs absorb infrared radiation, and the resulting temperature increase might be sufficient to negate the cooling caused by ozone depletion. Similarly, oxides of nitrogen absorb solar radiation so effectively that they are able to reduce the cooling caused by their destruction of ozone by about half (Ramanathan *et al.* 1976).

Changes in the earth's energy budget initiated by declining stratospheric ozone levels are integrated with changes produced by other elements such as atmospheric turbidity and the greenhouse effect. The specific effects of ozone depletion are therefore difficult to identify, and the contribution of ozone depletion to climatic change difficult to assess.

## THE MONTREAL PROTOCOL

In September 1987, thirty-one countries, meeting under the auspices of the United Nations Environment Program in Montreal, signed an agreement to protect the earth's ozone layer. The Montreal Protocol was the culmination of a series of events which had been initiated two years earlier at the Vienna Convention for the Protection of the Ozone Layer. Twenty nations signed the Vienna Convention in September 1985, promising international cooperation in research, monitoring and the exchange of information on the problem. In the two-year period between the meetings much time and effort went into formulating plans to control the problem, with the countries of the European Community (EC) favouring a relatively gradual approach compared to the more drastic suggestions of the North Americans (Tucker 1987). The Environmental Protection Agency (EPA) in the United States, against a background of an estimated 39 million additional cases of skin cancer in the next century, suggested a 95 per cent reduction in CFC production within a period of 6–8 years (Chase 1988). When the Montreal Protocol was signed, participants agreed to a 50 per cent production cut by the end of the century, although that figure is deceptive, since Third World countries were to be allowed to increase their use of CFCs for a decade to allow technological improvements in such areas as refrigeration. The net result turned out to be only a 35 per cent reduction in total CFC production by the end of the century, based on 1986 totals (Lemonick 1987). This was a historic agreement, but certain experts in the field, such as Sherwood Rowland, felt that it is not enough, and that the original 95 per cent proposed by the EPA was absolutely necessary (Lemonick 1987).

The signatories to the Montreal Protocol met again in Helsinki in May 1989. At that time, along with participants from some 50 additional countries, they agreed to the elimination of CFC production and use by the year 2000. Continued reassessment of the issue led to a further meeting of the world's environment ministers in Copenhagen in 1992, at which deadlines for the control of ozone-destroying gases were revised. In most cases—CFCs, carbon tetrachloride and methyl chloroform—production bans were brought forward from 2000 to 1996, but in the case of halons the ban was to be implemented by 1994 (see Table 6.2). HCFCs—widely used as substitutes for CFCs—were to be phased out progressively over a thirty-five-year period ending in 2030. Methyl bromide was added to the list of banned substances, with emissions to be frozen at the 1991 level by 1995 (MacKenzie 1992).

In contrast to their attitudes in the 1970s, the CFC manufacturers responded positively after Montreal to the call for a reduction in the manufacture of the chemical. The DuPont Company, for example, pledged to reduce its output by 95 per cent by the year 2000 (the original EPA suggestion), although the initial search for appropriate substitutes—which included testing for health and environmental effects—was estimated to take up to five years (Climate Institute 1988c). The market for substitutes is large, particularly in Europe, where CFCs were not banned in the 1970s. Although the concern for the supply of energy is no longer at crisis levels, the demand for residential and industrial building insulation remains high, and will undoubtedly rise if energy supplies are again threatened. Since the manufacture of insulating materials accounts for 28 per cent of worldwide CFC production, the search for alternatives received urgent attention. Results have been mixed. DuPont has developed hydrochlorofluorocarbons (HCFCs) as potential replacements for CFCs in the production of polystyrene sheet, which has been used successfully in food packaging, but is not suitable for other forms of insulation since the product loses its insulating ability as the HCFCs break down (Webster 1988). HCFCs are 95 per cent less damaging to ozone than normal CFCs because they are less stable and tend to break down in the troposphere before they can diffuse into the ozone layer. Although they are less harmful, they do have a negative impact on the ozone layer, and, as a result, they too will ultimately need to be replaced. An isocyanate-based insulation foam, in which carbon dioxide is the foaming agent, has produced promising results. It cannot be produced in sheet form, however, and, as a result, its use remains limited to situations where spray-on or foam-in application is possible.

Substitutes are being sought in other areas also. For example a German company has developed a so-called ‘green’ refrigerator, in which the normal CFC refrigerant is replaced by a propane/butane mixture. Although the mixture has a greater cooling capacity than the CFCs currently used, inefficiencies in the compressor system require attention before the refrigerator can compete with conventional units. Bans on the use of hydrocarbons in domestic refrigerators in some countries will also limit its adoption (Toro 1992). More damaging to the ozone than most CFCs are the halons used in fire-fighting—Halon 1301, for example is ten times more destructive than CFC-11—and replacements are required to meet the 1994 ban on halon production agreed at Copenhagen in 1992. To meet that need, a new gas mixture consisting of nitrogen, argon and carbon dioxide has been developed in Britain. None of these gases damages ozone, and existing fire extinguishing systems can be modified to use the mixture (Tickell 1992). Clearly, CFC manufacturing companies, and those utilizing gases hazardous to ozone, are committed to the search for alternatives, but it may be some time before their good intentions are translated into a suitable product.

## SUMMARY

There is an ever-increasing amount of evidence that the earth’s ozone layer is being depleted, allowing a higher proportion of ultraviolet radiation to reach the earth’s surface. If allowed to continue, this would cause a serious increase in skin cancer cases, produce more eye disease and change the genetic make-up of terrestrial organisms. In addition, since ultraviolet radiation is an integral part of the earth’s energy budget, any increase in its penetration to the lower atmosphere could lead to climatic change. The effects of a depleted ozone layer are widely accepted, but the extent of the depletion and its cause are still not completely understood. This reflects society’s inadequate knowledge of the workings of the earth/atmosphere system in general, and the photochemistry of the stratosphere in particular. It may take many years of observation and research before this situation is altered, but in the meantime a general concensus among scientists and politicians, that CFCs are the main culprits in the destruction of the earth's ozone, has led to the proscription of that group of chemicals. By the end of this century, CFCs will no longer be produced, but their effects will linger on until those presently in the atmosphere are gone.

In dealing with the global aspects of air pollution involving such elements as acid precipitation, atmospheric turbidity and the threat to the ozone layer, it is quite clear that although society now has the ability to cause all of these problems, and may even possess the technology to slow down and reverse them, its understanding of their overall impact on the earth/atmosphere system lags behind. Until that can be changed, the effects of human activities on the system will often go unrecognized, response to problems will of necessity be reactive, and the damage done before the problem is identified and analysed may be irreversible.

## SUGGESTIONS FOR FURTHER READING

Dotto, L. and Schiff, H. (1978) *The Ozone War,* Garden City: Doubleday.

Gribbin, J. (1993) *The Hole in the Sky,* (revised edition) New York: Bantam.

Nance, J.J. (1991) *What Goes Up: the Global Assault on our Atmosphere,* New York: W.Morrow.

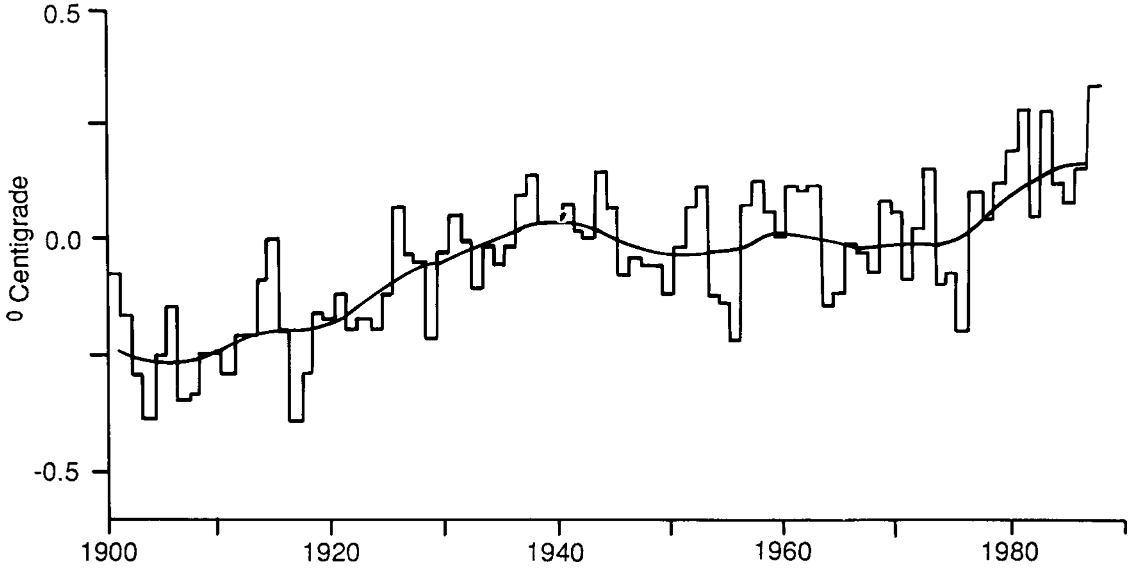
# 7

# The greenhouse effect and global warming

The succession of exceptional years with record high temperatures, which characterized the 1980s, helped to generate widespread popular interest in global warming and its many ramifications. The decade included six of the warmest years in the past century, and the trend continued into the 1990s, with 1991 the second warmest year on record. All of this fuelled speculation—especially among the media—that the earth's temperature had begun an inexorable rise, and the idea was further reinforced by the results of scientific studies which indicated that global mean temperatures had risen by about 0.5°C since the beginning of the century (see Figure 7.1).

Periods of rising temperature are not unknown in the earth's past. The most significant of these was the so-called Climatic Optimum, which occurred some 5,000–7,000 years ago and was associated with a level of warming that has not been matched since. If the current global warming continues, however, the record temperatures of the earlier period will easily be surpassed. Temperatures reached during a later warm spell in the early Middle Ages may well have been equalled already. More recently, the 1930s

*Figure 7.1* Measured globally-averaged (i.e. land and ocean) surface air temperatures for this century




*Source:* After Jones and Henderson-Sellers (1990)

*Table 7.1* Sources of greenhouse gas emissions

| *Sectors* | *Activities* | *Gases* | *Percentage of global total* |
|---|---|---|---|
| Energy | Fossil fuel combustion | $CO_2$, $CH_4$, $N_2O$, $O_3$ | 54 |
| | Natural gas leakage | | |
| | Industrial activities | | |
| | Biomass burning | | 3 |
| Forest | Harvesting | $CO_2$, $CH_4$, $N_2O$ | |
| | Clearing | | 8 |
| | Burning | | |
| Agriculture | Rice production (paddies) | $CO_2$, $CH_4$, $N_2O$ | 4.5 |
| | Animal husbandry (ruminants) | | 3 |
| | Fertilizer use | | 1.5 |
| Waste management | Sanitary landfill waste disposal | $CO_2$, $CH_4$, $N_2O$, $O_3$, CFC | 5 |
| | Incineration | | |
| | Biomass decay | | |
| Other | Cement production | $CO_2$, $N_2O$, CFC | 1 |
| | CFC production/use | | 11.5 |
| | Miscellaneous | | 8.5 |

*Source:* After Green and Salt (1992)

provided some of the highest temperatures since records began, although that decade has been relegated to second place by events in the 1980s. Such warm spells have been accepted as part of the natural variability of the earth/ atmosphere system in the past, but the current warming is viewed in a different light. It appears to be the first global warming to be created by human activity.

The basic cause is seen as the enhancement of the greenhouse effect, brought on by rising levels of anthropogenically-produced greenhouse gases (see Table 7.1). It is now generally accepted that the concentrations of greenhouse gases in the atmosphere have been increasing since the latter part of the nineteenth century. The increased use of fossil fuels has released large amounts of $CO_2$, and the destruction of natural vegetation has prevented the environment from restoring the balance. Levels of other greenhouse gases, including $CH_4$, $N_2O$ and CFCs have also been rising. Since all of these gases have the ability to retain terrestrial radiation in the atmosphere, the net result should be a gradual increase in global temperatures. The link between recent warming and the enhancement of the greenhouse effect seems obvious. Most of the media, and many of those involved in the investigation and analysis of global climate change, seem to have accepted the relationship as a *fait accompli*. There are only a few dissenting voices, expressing misgivings about the nature of the evidence and the rapidity with which it has been embraced. A survey of environmental scientists involved in the study of the earth's changing climate, conducted in the spring of 1989, revealed that many still had doubts about the extent of the warming. More than 60 per cent of those questioned indicated that they were not completely confident that the current warming was beyond the range of normal natural variations in global temperatures (Slade 1990).

## THE CREATION OF THE GREENHOUSE EFFECT

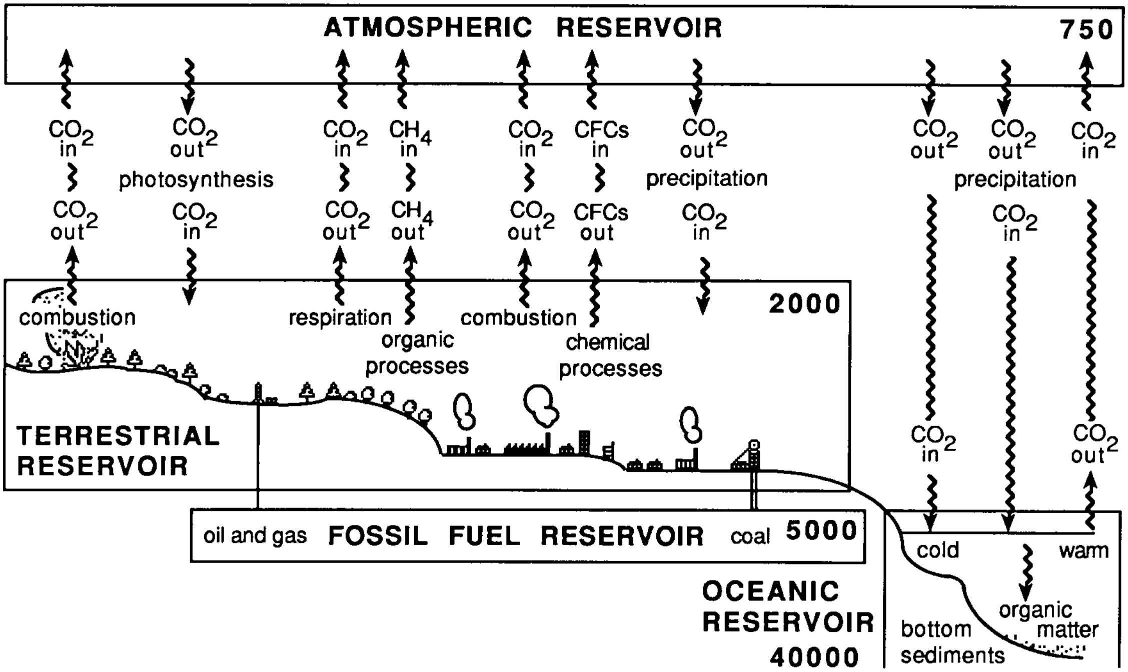
The greenhouse effect is brought about by the ability of the atmosphere to be selective in its response to different types of radiation. The atmosphere readily transmits solar radiation—which is mainly short-wave energy from the ultraviolet end of the energy spectrum—allowing it to pass through unaltered to heat the earth's surface. The energy absorbed by the earth is reradiated into the atmosphere, but this terrestrial radiation is long-wave infrared, and instead of being transmitted it is absorbed, causing the temperature of the atmosphere to rise. Some of the energy absorbed in the atmosphere is returned to the earth's surface, causing its temperature to rise also (see Chapter 2). This is considered similar to the way in which a greenhouse works—allowing sunlight in, but trapping the resulting heat inside—hence the use of the name 'greenhouse effect'. In reality it is the glass in the greenhouse which allows the temperature to be maintained, by preventing the mixing of the warm air inside with the cold air outside. There is no such barrier to mixing in the real atmosphere, and some scientists have suggested that the processes are sufficiently different to preclude the use of the term 'greenhouse effect'. Anthes *et al.* (1980) for example, prefer to use 'atmospheric effect'. However, the use of the term 'greenhouse effect' to describe the ability of the atmosphere to absorb infrared energy is so well established that any change would cause needless confusion. The demand for change is not strong, and 'greenhouse effect' will continue to be used widely for descriptive purposes, although the analogy is not perfect.

Without the greenhouse effect, global temperatures would be much lower than they are—perhaps averaging only -17°C compared to the existing average of +15°C. This, then, is a very important characteristic of the atmosphere, yet it is made possible by a group of gases which together make up less than 1 per cent of the total volume of the atmosphere. There are about twenty of these greenhouse gases. Carbon dioxide is the most abundant, but methane, nitrous oxide, the chlorofluorocarbons and tropospheric ozone are potentially significant, although the impact of the ozone is limited by its variability and short life span. Water vapour also exhibits greenhouse properties, but it has received less attention in the greenhouse debate than the other gases since the very efficient natural recycling of water through the hydrologic cycle ensures that its atmospheric concentration is little affected by human activities. Any change in the volume of the greenhouse gases will disrupt the energy flow in the earth/atmosphere system, and this will be reflected in changing world temperatures. This is nothing new. Although the media sometimes seem to suggest that the greenhouse effect is a modern phenomenon, it is not. It has been a characteristic of the atmosphere for millions of years, sometimes more intense than it is now, sometimes less.

### The carbon cycle and the greenhouse effect

Three of the principal greenhouse gases—$CO_2$, methane ($CH_4$) and the CFCs—contain carbon, one of the most common elements in the environment, and one which plays a major role in the greenhouse effect. It is present in all organic substances, and is a constituent of a great variety of compounds, ranging from relatively simple gases to very complex derivatives of petroleum hydrocarbons. The carbon in the environment is mobile, readily changing its affiliation with other elements in response to biological, chemical and physical processes. This mobility is controlled through a natural biogeochemical cycle which works to maintain a balance between the release of carbon compounds from their sources and their absorption in sinks. The natural carbon cycle is normally considered to be self-regulating, but with a time scale of the order of thousands of years. Over shorter periods, the cycle appears to be unbalanced, but that may be a reflection of an incomplete understanding of the processes involved or perhaps an indication of the presence of sinks or reservoirs still to be discovered (Moore and Bolin 1986). The carbon in the system moves

*Figure 7.2* Schematic representation of the storage and flow of carbon in the earth/atmosphere system




*Source*: Compiled from data in Gribbin (1978), McCarthy *et al.* (1986)

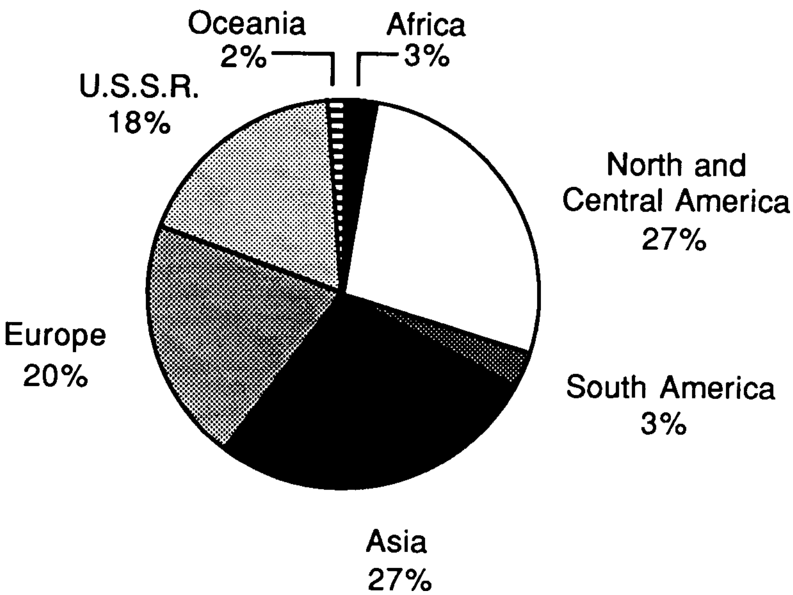
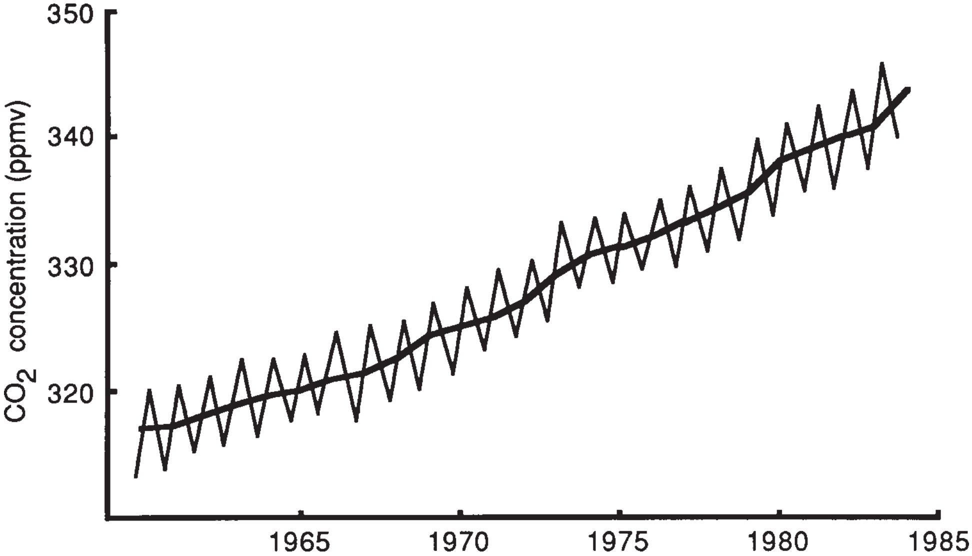



*Figure 7.3* $CO_2$ emissions: percentage share by region

*Source:* Based on data in World Resources Institute (1992)

*Figure 7.4* Rising levels of atmospheric $CO_2$ at Mauna Loa, Hawaii. The smooth curve represents annual average values; the zig-zag curve indicates seasonal fluctuations. The peaks in the zig-zag curve represent the winter values and the troughs represent the summer values

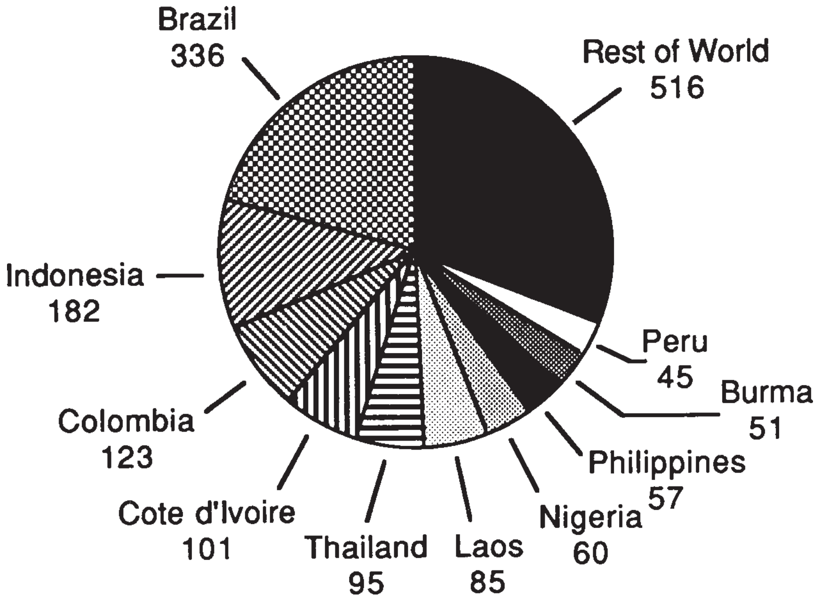



*Source:* After Bolin *et al.* (1986)

between several major reservoirs (see Figure 7.2). The atmosphere, for example, contains more than 750 billion tonnes of carbon at any given time, while 2,000 billion tonnes are stored on land, and close to 40,000 billion tonnes are contained in the oceans (Gribbin 1978). Living terrestrial organic matter is estimated to contain between 450 and 600 billion tonnes, somewhat less than that stored in the atmosphere (Moore and Bolin 1986). World fossil fuel reserves also constitute an important carbon reservoir of some 5,000 billion tonnes (McCarthy *et al.* 1986). They contain carbon which has not been active in the cycle for millions of years, but is now being reintroduced as a result of the growing demand for energy in modern society being met by the mining and burning of fossil fuels. It is being reactivated in the form of $CO_2$, which is being released into the atmospheric reservoir in quantities sufficient to disrupt the natural flow of carbon in the environment. The greatest natural flow (or flux) is between the atmosphere and terrestrial biota and between the atmosphere and the oceans (Watson *et al.* 1990). Although these fluxes vary from time to time, they have no long-term impact on the greenhouse effect because they are an integral part of the earth/atmosphere system. In contrast, inputs to the atmosphere from fossil fuel consumption, although smaller than the natural flows, involve carbon which has not participated in the system for millions of years. When it is reintroduced, the system cannot cope immediately, and becomes unbalanced. The natural sinks are unable to absorb the new $CO_2$ as rapidly as it is being produced. The excess remains in the atmosphere, to intensify the greenhouse effect, and thus contribute to global warming.

The burning of fossil fuels adds more than 5 billion tonnes of $CO_2$ to the atmosphere every year (Keepin *et al.* 1986), with more than 90 per cent originating in North and Central America, Asia, Europe and the republics of the former USSR (see Figure 7.3). Fossil fuel use remains the primary source of anthropogenic $CO_2$ but augmenting that is the destruction of natural

*Figure 7.5* Net regional release of carbon to the atmosphere as a result of deforestation during the 1980s (teragrams of carbon)




*Source:* After Mintzer (1992)

vegetation which causes the level of atmospheric $CO_2$ to increase by reducing the amount recycled during photosynthesis. Photosynthesis is a process, shared by all green plants, by which solar energy is converted into chemical energy. It involves gaseous exchange. During the process, $CO_2$ taken in through the plant leaves is broken down into carbon and oxygen. The carbon is retained by the plant while the oxygen is released into the atmosphere. The role of vegetation in controlling $CO_2$ through photosynthesis is clearly indicated by variations in the levels of the gas during the growing season. Measurements at Mauna Loa Observatory in Hawaii show patterns in which $CO_2$ concentrations are lower during the northern summer and higher during the northern winter (see Figure 7.4). These variations reflect the effects of photosynthesis in the northern hemisphere, which contains the bulk of the world's vegetation (Bolin 1986). Plants absorb $CO_2$ during their summer growing phase, but not during their winter dormant period, and the difference is sufficient to cause semi-annual fluctuations in global $CO_2$ levels.

The clearing of vegetation raises $CO_2$ levels indirectly through reduced photosynthesis, but $CO_2$ is also added directly to the atmosphere by burning, by the decay of biomass and by the increased oxidation of carbon from the newly exposed soil. Such processes are estimated to be responsible for 5–20 per cent of current anthropogenic $CO_2$ emissions (Waterstone 1993). This is usually considered a modern phenomenon, particularly prevalent in the tropical rainforests of South America and South-East Asia (Gribbin 1981) (see Figure 7.5), but Wilson (1978) has suggested that the pioneer agricultural settlement of North America, Australasia and South Africa in the second half of the nineteenth century made an important contribution to rising $CO_2$ levels. This is supported to some extent by the observation that between 1850 and 1950 some 120 billion tonnes of carbon were released into the atmosphere as a result of deforestation and the destruction of other vegetation by fire (Stuiver 1978). The burning of fossil fuels produced only half that much $CO_2$ over the same time period. Current estimates indicate that the atmospheric $CO_2$ increase resulting from reduced photosynthesis and the clearing of vegetation is equivalent to about 1 billion tonnes per year (Moore and Bolin 1986), down slightly from the earlier value. However, the annual contribution from the burning of fossil fuels is almost ten times what it was in the years between 1850 and 1950.

Although the total annual input of $CO_2$ to the atmosphere is of the order of 6 billion tonnes, the atmospheric $CO_2$ level increases by only about 2.5 billion tonnes per year. The difference is distributed to the oceans, to terrestrial biota and to other sinks as yet unknown (Moore and Bolin 1986). Although the oceans are commonly considered to absorb 2.5 billion tonnes of $CO_2$ per year, recent studies suggest that the actual total may be only half that amount (Taylor 1992). The destination of the remainder has important implications for the study of the greenhouse effect, and continues to be investigated. The oceans absorb the $CO_2$ in a variety of ways—some as a result of photosynthesis in phytoplankton, some through nutritional processes which allow marine organisms to grow calcium carbonate shells or skeletons, and some by direct diffusion at the air/ocean interface (McCarthey *et al.* 1986). The mixing of the ocean waters causes the redistribution of the absorbed $CO_2$. In polar latitudes, for example, the added carbon sinks along with the cold surface waters in that region, whereas in warmer latitudes carbon-rich waters well up towards the surface allowing the $CO_2$ to escape again. The turnover of the deep ocean waters is relatively slow, however, and carbon carried there in the sinking water or in the skeletons of dead marine organisms remains in storage for hundreds of years. More rapid mixing takes place through surface ocean currents such as the Gulf Stream, but in general the sea responds only slowly to changes in atmospheric $CO_2$ levels. This may explain the apparent inability of the oceans to absorb more than 40–50 per cent of the $CO_2$ added to the atmosphere by human activities, although it has the capacity to absorb all of the additional carbon (Moore and Bolin 1986).

The oceans constitute the largest active reservoir of carbon in the earth/atmosphere system, and their ability to absorb $CO_2$ is not in doubt. However, the specific mechanisms involved are now recognized as extremely complex, requiring more research into the interactions between the atmosphere, ocean and biosphere if they are to be better understood (Crane and Liss 1985).

## The changing greenhouse effect

Palaeoenvironmental evidence suggests that the greenhouse effect fluctuated quite considerably in the past. In the Quaternary era, for example, it was less intense during glacial periods than during the interglacials (Bach 1976; Pisias and Imbrie 1986). Present concern is with its increasing intensity and the associated global warming. The rising concentration of atmospheric $CO_2$ is usually identified as the main culprit, although it is not the most powerful of the greenhouse gases. It is the most abundant, however, and its concentration is increasing rapidly. As a result, it is considered likely to give a good indication of the trend of the climatic impact of the greenhouse effect, if not its exact magnitude.

Svante Arrhenius, a Swedish chemist, is usually credited with being the first to recognize that an increase in $CO_2$ would lead to global warming (Bolin 1972; Bach 1976; Crane and Liss 1985). Other scientists, including John Tyndall in Britain and T.C.Chamberlin in America (Jones and Henderson-Sellers 1990), also investigated the link, but Arrhenius provided the first quantitative predictions of the rise in temperature (Idso 1981; Crane and Liss 1985). He published his findings at the beginning of this century, at a time when the environmental implications of the Industrial Revolution were just beginning to be appreciated. Little attention was paid to the potential impact of increased levels of $CO_2$ on the earth's radiation climate for some time after that, however, and the estimates of $CO_2$-induced temperature increases calculated by Arrhenius in 1903 were not bettered until the early 1960s (Bolin 1972). Occasional papers on the topic appeared (e.g. Callendar 1938; Revelle and Seuss 1957; Bolin 1960), but interest only began to increase significantly in the early 1970s, as part of a growing appreciation of the potentially dire consequences of human interference in the environment. Increased $CO_2$ production and rising atmospheric turbidity were recognized as two important elements capable of causing changes in climate. The former had the potential to cause greater warming, whereas the latter was considered more likely to cause cooling (Schneider and Mesirow 1976). For a time it seemed that the cooling would dominate (Calder 1974, Ponte 1976), but results from a growing number of investigations into greenhouse warming, published in the early 1980s, changed that (e.g. Idso 1980; Manabe *et al.* 1981; Schneider and Thompson 1981; Pittock and Salinger 1982; Mitchell 1983; NRC 1982 and 1983). They revealed that scientists had generally underestimated the speed with which the greenhouse effect was intensifying, and had failed to appreciate the impact of the subsequent global warming on the environment or on human activities.

Worldwide concern, coupled with a sense of urgency uncommon in the scientific community, led to a conference on the 'International Assessment of the Role of Carbon Dioxide and other Greenhouse Gases in Climate Variations and Associated Impact', held at Villach, Austria in October 1985. To ensure the follow-up of the recommendations of that conference, an Advisory Group on Greenhouse Gases (AGGG) was established under the auspices of the International Council of Scientific Unions (ICSU), the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) (Environment Canada 1986). The main tasks of the AGGG were to carry out biennial reviews of international and regional studies related to the greenhouse gases, to conduct aperiodic assessments of the rates of increases in the concentrations of greenhouse gases, and to estimate the effects of such increases. Beyond this, they also supported further studies of the socio-economic impacts of climatic change produced by the greenhouse gases, and identified areas such as the monsoon region of south-east Asia, the Great Lakes region of North America and the circumpolar Arctic as likely candidates for increased investigation. The AGGG suggested that the dissemination of information on recent developments to a wide audience was also important, and in keeping with that viewpoint Environment Canada began the production of a regular newsletter to highlight current events in $CO_2$/climate research. Its annual reports *Understanding $CO_2$ and Climate,* published in 1986 and 1987, were also devoted to that theme. Throughout the 1980s, Environment Canada funded research on the environmental and socio-economic impacts of global warming in such areas as agriculture, natural resource development and recreation and tourism. The Department of Energy in the United States has also been active in the field with more broadly based reports on the effects of increasing $CO_2$ levels on vegetation (Strain and Cure 1985) and on climate (MacCracken and Luther 1985a and 1985b) as well as the effects of future energy use and technology on the emission of $CO_2$ (Edmonds *et al.* 1986; Cheng *et al.* 1986).

In Europe, Flohn's (1980) study of the climatic consequences of global warming caused by human activities, for the International Institute for Applied Systems Analysis (IIASA), included consideration of $CO_2$. More recently, the Commission of European Communities (CEC) funded research into the socio-economic impacts of climate changes which might be caused by a doubling of atmospheric $CO_2$ (Meinl *et al.* 1984; Santer 1985). Most of these investigations involved the use of GCMs. The UK Meteorological Office five-layer GCM, for example, provided information on $CO_2$-induced climatic change over western Europe (Wilson and Mitchell 1987). Several other European countries, including Germany and the Netherlands, also launched research programmes.

*Table 7.2* A condensation of the IPCC Executive Summary on Climate Change: 1990

*Certainties*
(a) There is a natural greenhouse effect which keeps the earth warmer than it would otherwise be.
(b) The natural greenhouse effect is being enhanced by increasing atmospheric concentrations of greenhouse gases – $CO_2$, $CH_4$, $N_2O$, CFCs, $H_2O$.

*Calculations*
(a) Some greenhouse gases are more effective than others in causing climate change. For example, $CO_2$ has been responsible for more than half the enhanced greenhouse effect in the past, and that situation is unlikely to change.
(b) Atmospheric concentrations of long-lived gases adjust only slowly to changing emissions. Thus, the longer emissions continue at current rates, the greater will be the reductions required to stabilize concentrations at a given level.
(c) Immediate reductions of over 60 per cent in the emissions of long-lived gases would be required to stabilize their concentrations at present levels.

*Predictions – based on current model results*
(a) Under the IPCC 'business-as-usual' scenario, mean global temperatures will rise by about 0.3°C per decade. The rise will not be steady, but the prediction is an increase in mean global temperatures of about 1°C above present values by 2025 and 3°C by 2100.
(b) Increasingly stringent emission controls could reduce the temperature increase to between 0.1°C and 0.2°C per decade.
(c) Land surfaces will warm more than the oceans and high northern latitudes will warm more than the global mean in winter.
(d) Regional temperature changes will differ significantly from the global mean, although confidence in the predictions is low because of the inaccuracy of GCMs at regional scales.
(e) Global mean sea level will rise about 20 cm by 2030 and 65 cm by 2100, but with significant regional variations.

*Uncertainties in the predictions*
Predictions of the timing, magnitude and regional patterns of climate change are hampered by incomplete understanding of:
- sources and sinks of greenhouse gases
- clouds
- oceans
- polar ice sheets

*Improvements to the predictions*
To improve current predictive capability, it will be necessary to:
- understand better the climate related processes associated with clouds, oceans and the carbon cycle.
- improve systematic global observation of climate-related variables and further investigate past changes.
- develop improved climate models.
- increase support for climate research activities, especially in developing countries.
- facilitate international exchange of climate data.

*Source:* Houghton *et al.* (1990)

With the worldwide increase in the number of government agencies involved in the study of global warming, it became clear that an attempt had to be made to assess the overall state of the research. This was made possible by the WMO and UNEP, which together established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC was charged with assessing the status of the scientific information on climate change so that potential environmental and socio-economic impacts could be evaluated. It was also asked to formulate appropriate response strategies. With the co-operation of several hundred scientists from around the world, the IPCC produced the first part of its report—the scientific assessment—in 1990 (Houghton *et al.* 1990). The reports on impact assessment (Tegart *et al.* 1990) and response strategies (IPCC 1991) followed shortly thereafter. The scientific assessment included a summary of current knowledge of global warming as well as predictions for future developments (see Table 7.2). A supplementary report was issued in 1992, generally confirming the results of the earlier assessment, but also paying greater attention to the effects of sulphate emissions and ozone depletion on global warming trends (Houghton *et al.* 1992).

Concern over global warming was also an integral part of the Framework Convention on Climate Change signed at the Earth Summit in Rio de Janeiro in 1992. The convention was intended to deal with the human contribution to global warming, and create a vehicle for international action comparable to the Montreal Protocol on ozone depletion. For most observers, however, it was no more than a symbolic statement with few specific targets and no proper enforcement mechanisms (Clery 1992; Hulme 1993). The refusal of the United States to agree to even modest greenhouse gas emission targets, and the unwillingness of some Third World countries to support the energy efficiency standards necessary for reduced emissions, further weakened the convention (Pearce 1992c).

The perceived weakness of the convention is in part a reflection of the different views of the issue held by policymakers and scientists (Leggett 1992). Despite the immense volume of research on global warming, many key elements—such as the magnitude and timing of the warming—remain imperfectly understood, and therefore difficult to predict with any accuracy. Uncertainty of this type is not uncommon in scientific research, and scientists have come to accept it, but among planners and politicians it is often seen as undermining the arguments of those calling for immediate attention to the issue. Since policymakers have the ultimate say in where and when policy will be implemented to deal with the warming, it appears that they must shoulder much of the blame for the delays. However, some environmentalists also claim that scientists have failed, by giving too much attention to the uncertainties and too little to the dire consequences of full-scale warming (Leggett 1992).

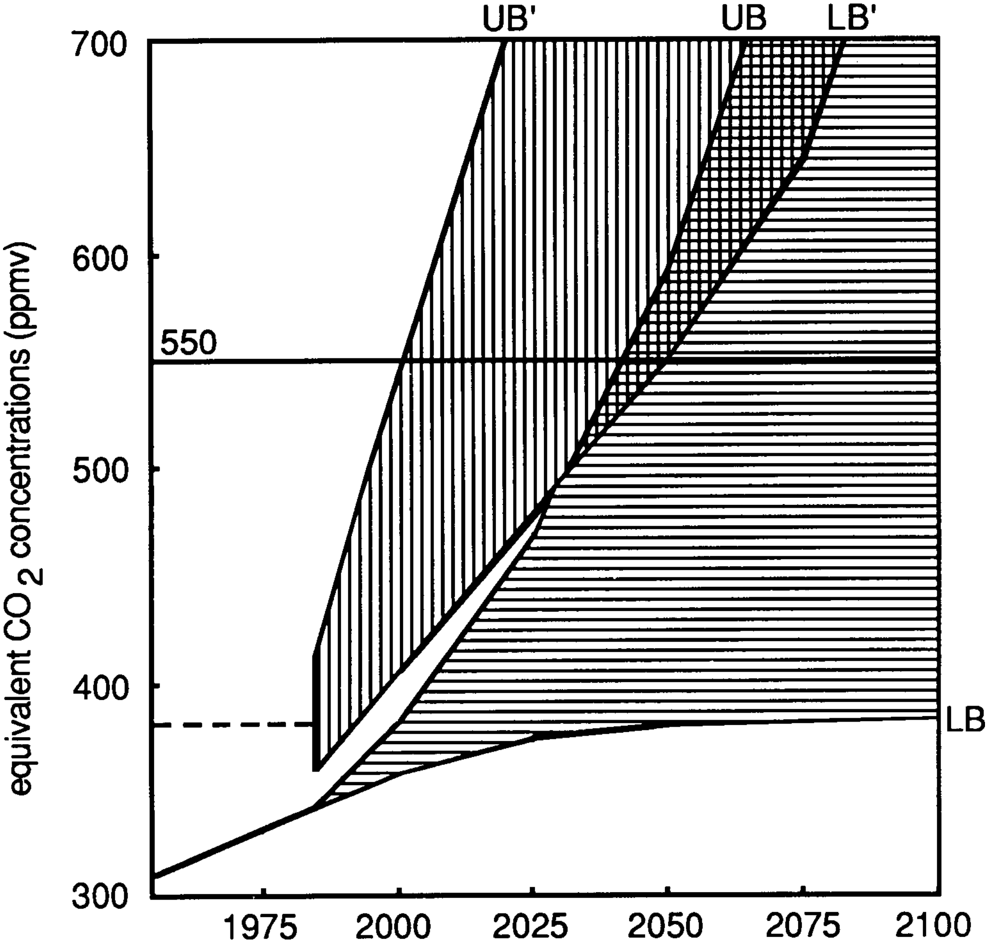
No matter how the blame is apportioned, one of the results of the uncertainty has been to allow those who remain unconvinced by the scientific assessment, or perhaps have a vested interest in retaining the *status quo,* to argue successfully that no steps be taken to deal with the issue until the real impact of global warming is revealed by additional research. That may yet take several decades, and some of the researchers investigating the problem warn that by then it may be too late (Roberts 1989; Henderson-Sellers 1990).

## Atmospheric carbon dioxide and temperature change

Although present concern with global warming centres on rising concentrations of atmospheric $CO_2$, concentrations of that gas have varied considerably in the past. Analysis of air bubbles trapped in polar ice indicates that the lowest levels of atmospheric $CO_2$ occurred during the Quaternary glaciations (Delmas *et al.* 1980). At that time, the atmosphere contained only 180 to 200 parts per million by volume (ppmv) of $CO_2$, although there is some evidence that levels fluctuated by as much as 60 ppmv in periods as short as 100 years (Crane and Liss 1985). Levels rose to 275 ppmv during the warm interglacial phases, and that level is also considered representative of the pre-industrial era of the early nineteenth century (Bolin 1986). $CO_2$ measurements taken by French scientists in the 1880s, just as the effects of the Industrial Revolution were beginning to be felt, have been reassessed by Siegenthaler (1984), who has concluded that levels in the northern hemisphere averaged 285 to 290 ppmv at that time.

When the first measurements were made at Mauna Loa in 1957, concentrations had risen to 310 ppmv, and they continued to rise by just over 1 ppmv per year to reach 335 in 1980.

*Figure 7.6* Projected changes in atmospheric $CO_2$ concentration. The curves LB and UB indicate the range of estimates for $CO_2$ alone. LB' and UB' indicate the range of estimates when other greenhouse gases are included and expressed in $CO_2$ equivalents. The value 550 ppm corresponds to a doubling of pre-industrial $CO_2$ concentrations




*Source:* After Bolin *et al.* (1986)

Since then, levels have risen at a rate of 2 to 4 ppmv per year to reach a level of 345 ppmv by the mid-1980s (Gribbin 1981; Bolin 1986). That represents an increase of 70 ppmv in less than 200 years. The difference between glacial and inter-glacial periods was about the same, but then the time interval was measured in tens of thousands of years. The current level of 353 ppmv is 25 per cent higher than the preindustrial volume, and without precedent in the past 100,000 years of earth history (Watson *et al.* 1990). If the present rate of increase continues until the year 2050, it is estimated that the atmospheric $CO_2$ concentration will be 450 ppmv, and by 2075 it will be 500–600 ppmv, more than twice the 1800 level (Bolin 1986) (see Figure 7.6).

Predicting such trends is difficult. Future growth rates and concentrations will depend upon a variety of factors, including, for

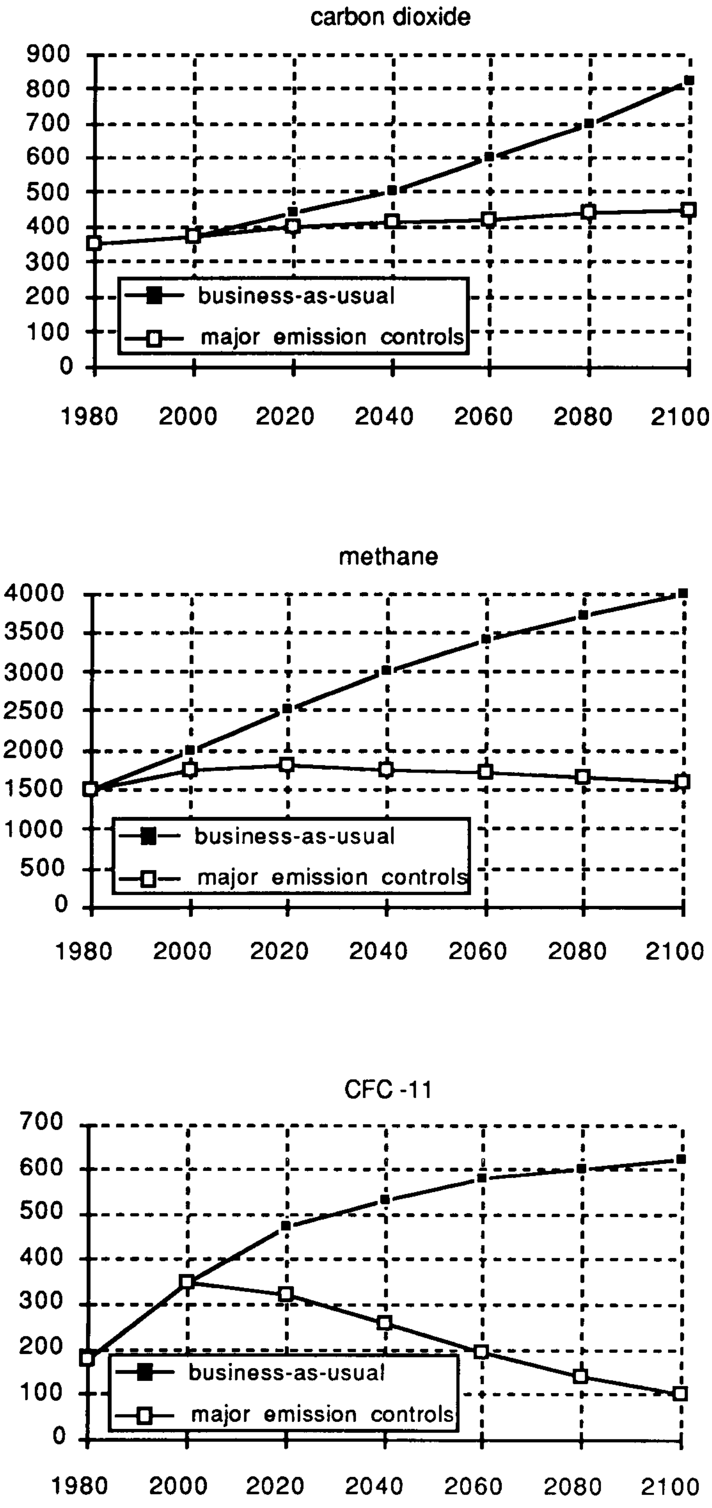



*Figure 7.7* Changing greenhouse gas levels: comparison of the 'business-as-usual' scenario with one involving major emission controls

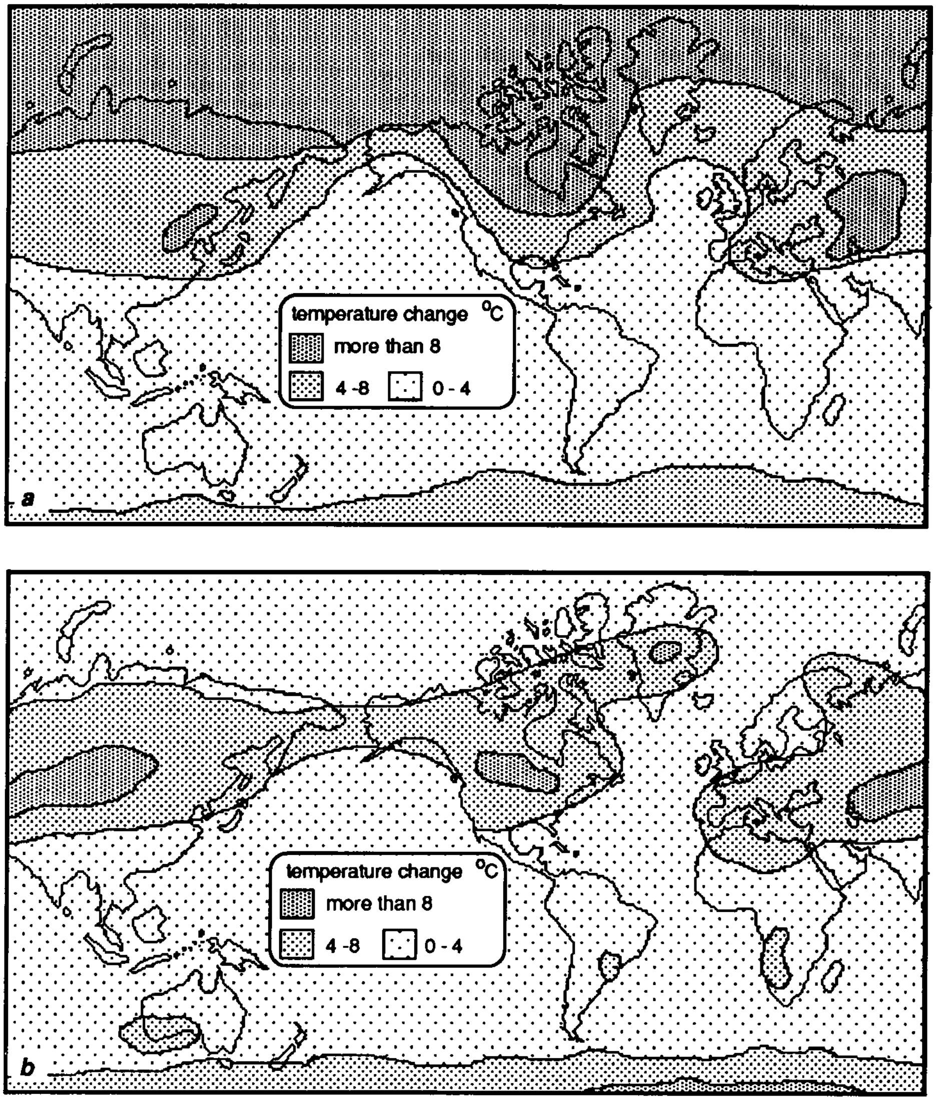
*Source:* After Houghton *et al.* (1990)

example, the nature and rate of industrial development, the extent to which the earth's forests continue to be destroyed and the success of programmes aimed at reducing the output of $CO_2$. Most studies have based their predictions on several scenarios, one of which is commonly a direct projection of the *status quo*—the IPCC 'business-as-usual' scenario, for example—with others based on either increase or decreases in $CO_2$ and combinations of other gases (Bolin *et al.* 1986, Houghton *et al.* 1990). The net result is that future greenhouse gas levels are usually presented as ranges of possibilities rather than discrete values (see Figure 7.7).

Since $CO_2$ is a radiative forcing agent known to warm the atmosphere, the rising $CO_2$ values can be translated into temperature increases. It has been estimated, for example, that a 0.3–0.6°C increase in the earth's surface temperature has taken place since 1900, at a rate broadly consistent with that expected from the rising levels of greenhouse gases (Houghton *et al.* 1990). Schneider (1987) claims that the earth is 0.5° warmer in the 1980s than it was in the 1880s. The change has not been even, however. The main increase took place between 1910 and 1940, and again after 1975 (Gadd 1992). Between 1940 and 1975, despite rising greenhouse levels, global temperatures declined, particularly in the northern hemisphere. In addition, analysis of the records suggests that the relatively rapid warming prior to 1940 was probably of natural origin (Folland *et al.* 1990). Such changes are well within the range of normal natural variations in global temperatures (Crane and Liss 1985), but Hansen and Lebedeff (1988) have calculated that the warming between the 1960s and 1980s was more rapid than that between the 1880s and 1940s, which suggests that the greenhouse warming may be beginning to emerge from the general background 'noise'. Hansen, of the Goddard Institute of Space Studies, claimed subsequently that the global greenhouse signal is sufficiently strong that a cause-and-effect relationship between the $CO_2$ increase and global warming can be inferred (Climate Institute 1988a). The controversy continues, however. Kheshgi and White (1993) concluded that it will not be possible to separate a greenhouse warming signal from the overall noise until more is known about the dimensions and causes of natural climate variability. Wigley and Barnett (1990), in their contribution to the IPCC Scientific Assessment, took the middle ground. They noted that there is as yet no evidence of an enhanced greenhouse effect in the observational record, but cautioned that this may be in part a function of the uncertainties and inadequacies in current investigative techniques. In short, although greenhouse-gas-induced warming may not have been detected, it does not follow that it does not exist.

Estimates of global warming are commonly obtained by employing atmospheric modelling techniques based on computerized General Circulation Models (GCMs) (see Table 2.4). To examine the impact of an enhanced greenhouse effect on temperature, for example, the $CO_2$ component in the model is increased to a specific level. The computer program is allowed to run until equilibrium is established among the various climatic elements included in the model and the new temperatures have been reached (see Figure 7.8). This approach had produced a general consensus by the mid-1980s, that a doubling of $CO_2$ levels would cause an average warming of 1.3–4°C (Manabe and Wetherald 1975; Cess and Potter 1984; Dickinson 1986; Bolin *et al.* 1986). The IPCC assessment produced values of 1.5–4.5°C, with a best estimate of 2.5°C. These results compare with the estimate of 4–6°C made by Arrhenius at the beginning of the century (Kellogg 1987). Smaller increases have been calculated by Newell and Dopplick (1979) who estimated that the temperatures above the tropical oceans would increase by only 0.03°C on average and by Idso (1980) who estimated a global increase of 0.26°C. These lower values are generally considered to be unrepresentative by most scientists investigating the problem, however (Cess and Potter 1984; Webster 1984).

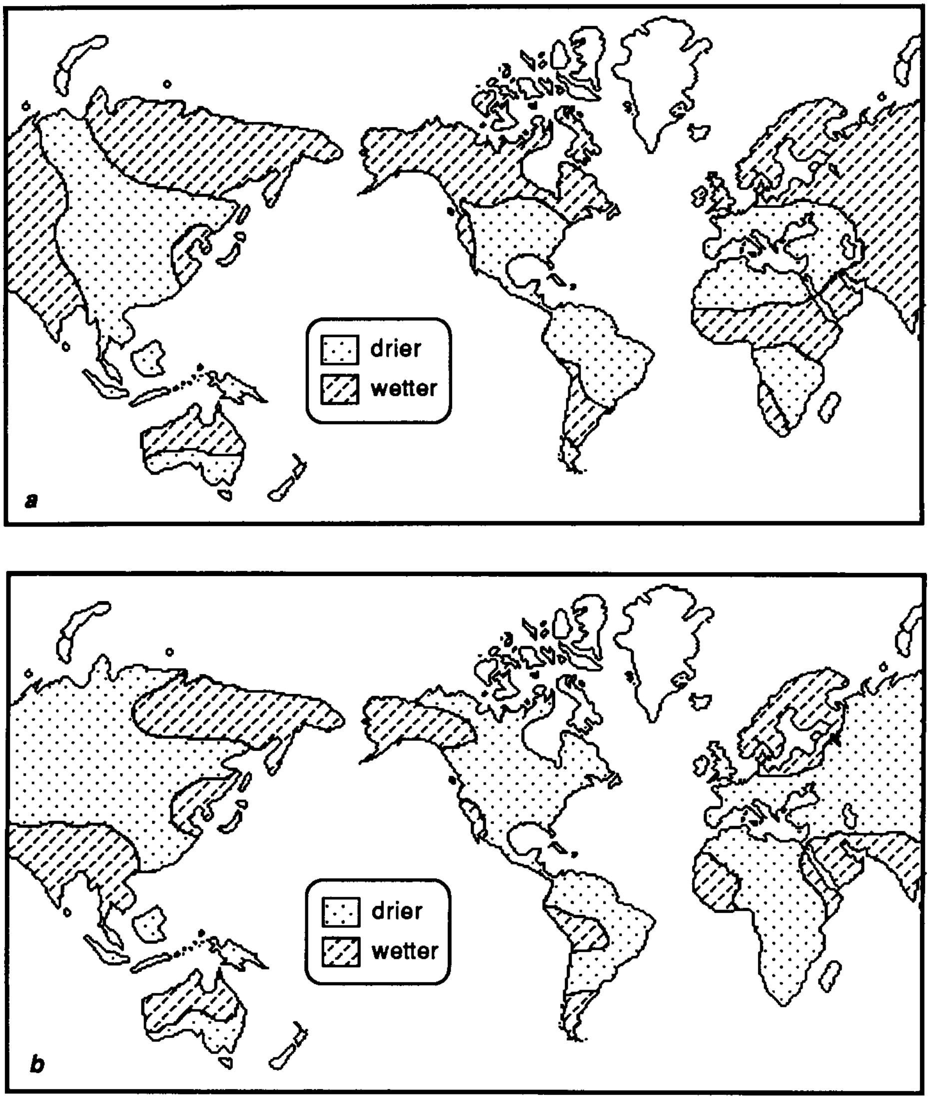
*Figure 7.8* Change in global surface temperature following a doubling of $CO_2$. (a) December, January and February, (b) June, July and August




*Source:* Compiled from data in Houghton *et al.* (1990)

Although the estimated temperature increases are not particularly impressive—mainly because they are average global values—evidence from past world temperature changes indicates that they are of a magnitude which could lead to significant changes in climate and climate-related activities. During the Climatic Optimum—the warm epoch following the last Ice Age—some 5,000 to 7,000 years ago, temperatures in North America and Europe were only 2–3°C higher than the present average, but they produced major environmental changes (Lamb 1977). Evidence from that time period, and from another warm spell in the early Middle Ages, 800 to 1,000

*Figure 7.9* Change in global soil moisture levels following a doubling of $CO_2$. (a) December, January and February, (b) June, July and August




*Source:* Compiled from data in Houghton *et al.* (1990)

years ago, also suggests that the greatest impact of any change will be felt in mid to high latitudes in the northern hemisphere.

The models used to investigate global change are usually considered to provide less accurate results at the regional level, but they do support these past geographical trends. Following a doubling of $CO_2$, the Canadian Climate Centre GCM indicates a warming of almost 5°C for the southern part of the country, summer and winter. In the north, the seasonal differences would be considerable, with a mean temperature increase of 8–12°C in winter, but less than 1°C in summer (Hengeveld 1991). Similar values are predicted for northern Russia, but in north-western Europe an annual increase of only 2–4°C is considered more likely (Mitchell *et al.* 1990). However, in the latter region, climate is strongly influenced by the north Atlantic oceanic circulation, and since reliable ocean/atmosphere models remain in the development stage, the accurate prediction of temperature change for such areas is difficult.

The estimated temperature increases at lower latitudes are generally less. According to predictions from China, temperatures will rise by 2–3°C in that country with increases exceeding 3°C only in the western interior (NCGCC 1990). In southern Europe, the Sahel, south-east Asia and Australia—all areas which received particular attention in the IPCC assessment—the predicted increases generally fall between 1–2°C, with only southern Europe expecting an increase of 3°C in the summer months (Mitchell *et al.* 1990).

Because the various elements in the atmospheric environment are closely interrelated, it is only to be expected that if temperature changes, changes in other elements will occur also. Moisture patterns are likely to be altered, for example (see Figure 7.9). In the mid-continental grasslands of North America, precipitation totals may be reduced by 10 to 20 per cent, while summer soil moisture levels may fall by as much as 50 per cent (Manabe and Wetherald 1986). IPPC estimates are slightly less, with summer precipitation declining by 5–10 per cent and soil moisture by 15–20 per cent, but confidence in these values is low (Mitchell *et al.* 1990). In northern and north-western China—where an average temperature increase of 2°C is expected—evaporation rates would increase by about 20 per cent, compounding existing problems of aridity in these areas (NCGCC 1990). Precipitation would be less frequent over most of Europe in summer and autumn, and throughout the year in the south (Wilson and Mitchell 1987), causing soil moisture levels to decline by as much as 25 per cent (Mitchell *et al.* 1990). According to some projections, more rainfall is possible in parts of Africa and southeast Asia (Wigley *et al.* 1986; Kellogg 1987). The latter would benefit from increases of up to 10 per cent in soil moisture during the summer months, but in parts of Africa such as the Sahel—where temperatures are expected to rise no more than 2°C—winter rainfall would decline by 5–10 per cent and summer precipitation increases of as much as 5 per cent would be insufficient to prevent a decline in soil moisture (Mitchell *et al.* 1990). Changes such as these in moisture regimes coupled with changes in the length and intensity of the growing season, would disrupt existing vegetation patterns, and require major alterations in agricultural activities in many areas.

The reality of the situation may only become apparent when the changes have occurred, for there are many variables in the predictions. The human factors, as always, are particularly unpredictable. Technology, politics, socio-economic conditions and even demography can contribute to changes in the concentration of $CO_2$, yet the nature and magnitude of the variations in these elements is almost impossible to predict.

## The contribution of other greenhouse gases

Most predictions of future changes in the intensity of the greenhouse effect are based solely on changes in the $CO_2$ content of the atmosphere. Their accuracy is therefore questionable, since $CO_2$ is not the only greenhouse gas, nor is it the most powerful. Methane ($CH_4$), nitrous oxide ($N_2O$) and the CFCs are the most important of the other greenhouse gases. Tropospheric ozone ($O_3$) is also capable of enhancing the greenhouse effect, but its present concentrations are very variable in both time and place, and there is no clear indication of future trends (Bolle *et al.* 1986).

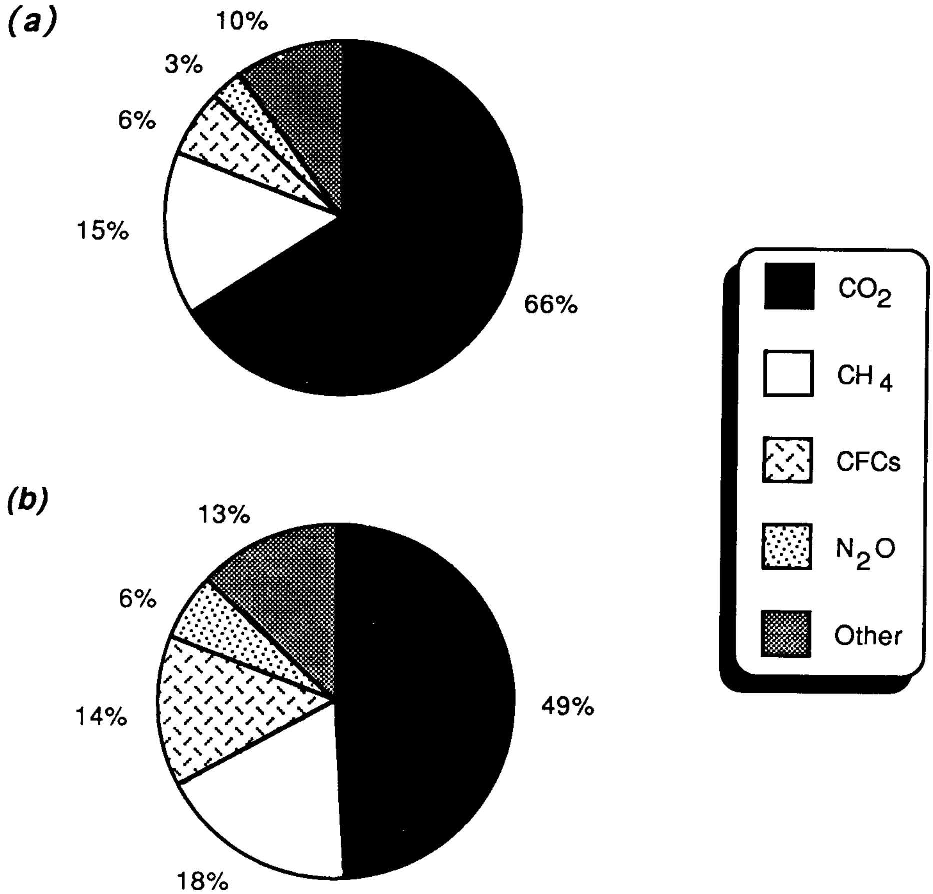
Methane is a natural component of the earth/atmosphere system with its origin in the anaerobic decay of organic matter, mainly in the earth's natural wetlands. Significant amounts of $CH_4$ are also produced by the global termite population (Crutzen et al. 1986). Levels of atmospheric $CH_4$—at 1.72 ppmv—are very low compared to those of $CO_2$. Molecule for molecule it is about twenty-one times more effective than $CO_2$, however, and its concentration is increasing at about 0.8–1.0 per cent per year (Blake and Rowland 1988; Shine *et al.* 1990). The most important causes of this increase are to be found in agricultural development (see Table 7.1). Biomass burning, to clear land for cultivation, adds $CH_4$ to the atmosphere, as does the world's growing population of domestic cattle, pigs and sheep, which release considerable amounts of $CH_4$ through their digestive processes (Crutzen *et al.* 1986). By far the largest source of agriculturally-produced $CH_4$, however, is rice cultivation. Rice paddies, being flooded and therefore providing an anaerobic environment for at least part of the year, act much like natural wetlands. Their total contribution to rising $CH_4$ levels is difficult to measure since 60 per cent of the world's rice paddies are in India and China—both areas from which reliable data are generally unavailable. However, annual rice production has doubled over the past 50 years, and it is likely that $CH_4$ emissions have increased in proportion (Watson *et al* 1990), although perhaps not by as much as was once thought (Houghton 1992).

The energy industry is another important source of anthropogenic $CH_4$. As a by-product of the conversion of vegetable matter into coal, it is trapped in coal-bearing strata, to be released into the atmosphere when coal is mined. It is also one of the main components of natural gas, and escapes during drilling operations or through leaks in pipelines and at pumping stations (Cicerone and Oremland 1988). Together these sources may account for 15 per cent of global $CH_4$ emissions (Hengeveld 1991). The disposal of organic waste in landfill sites, where it undergoes anaerobic decay, is also considered to be a potentially significant source of $CH_4$. Attempts to provide accurate estimates of emissions, however, are hampered by the absence of appropriate data on the nature and amounts of organic waste involved (Bingemer and Crutzen 1987).

The lifespan of $CH_4$ in the atmosphere averages 10 years. It is removed by reaction with hydroxyl radicals (OH) which oxidize it to water vapour and $CO_2$, both of which are greenhouse gases, but less potent than $CH_4$ (Watson *et al.* 1990). Atmospheric OH levels are currently declining as a result of reactions with other anthropogenically produced gases such as carbon monoxide (CO), causing a reduction in the rate of removal of $CH_4$ (Hengeveld 1991). The total impact of decreased concentrations is difficult to assess, but $CH_4$ emissions into the atmosphere continue to grow, and it has been estimated that an immediate reduction in emissions of 15–20 per cent would be required to stabilize concentrations at their current levels (Watson *et al.* 1990). The IPCC Supplementary Report noted some evidence that the rate of growth in $CH_4$ concentration in the atmosphere may be already beginning to slow down (Houghton 1992). Even with this, however, potential feedbacks working through such elements as soil moisture levels and rising high latitude temperatures, could result in significant increases in future $CH_4$ emissions. All of these trends suggest that $CH_4$ will continue to contribute to the enhancement of the greenhouse effect well into the future.

The current atmospheric concentration of $N_2O$—at 310 parts per billion by volume (ppbv)—is about a thousand times less than that of $CO_2$, and it is increasing less rapidly than either $CO_2$ or $CH_4$. $N_2O$ is released naturally into the atmosphere through the denitrification of soils, and is removed mainly through photochemical decompostion in the stratosphere, in a series of reactions which contribute to the destruction of the ozone layer (see Chapter 6). It is thought to owe its present growth to the increased use of fossil fuels and the denitrification of agricultural fertilizers. The IPCC assessment has concluded, however, that past estimates of the contribution of fossil fuel combustion to the increase are too large—by perhaps as much as ten times—and $N_2O$ production rates during agricultural activity are difficult to quantify. Thus, although the total increase of $N_2O$ can be calculated, the amounts attributable to specific sources cannot be predicted with any accuracy. It is even possible

*Figure 7.10* Greenhouse gas contributions to global warming (a) 1880–1980 (b) 1980s




*Source:* After Mintzer (1992)

that there are sources yet to be identified (Watson *et al.* 1990). As a result the global $N_2O$ budget remains poorly understood, and its future concentration is therefore difficult to predict.

CFCs and other halocarbons released from refrigeration units, insulating foams, aerosol spray cans and industrial plants are recognized for their ability to destroy the stratospheric ozone layer, but they are also among the most potent greenhouse gases. For example, CFC-11 is about 12,000 times more effective than $CO_2$ (Houghton *et al.* 1990). The CFCs are entirely anthropogenic in origin, and should therefore be much easier to monitor and control than some of the other gases. Their concentrations in the atmosphere range from CFC-115 at 5 parts per trillion by volume (pptv) to CFC-12 at 484 pptv, and have been growing at rates between 4–10 per cent per annum. Other halocarbons, such as Halon-1211 and Halon-1301, used mainly in fire extinguishers, with current concentrations of less than 2 pptv are growing at rates as high as 15 per cent per year (Watson *et al.* 1990). Recent international agreements to reduce the use of

CFCs (see Chapter 6) are aimed at preventing further damage to the ozone layer, but they will also have some impact on the greenhouse effect. However, CFCs have a long residence time in the atmosphere—up to 400 years in the case of CFC-13 and CFC-115—and even as emission rates fall, they will continue to contribute to global warming for some time to come.

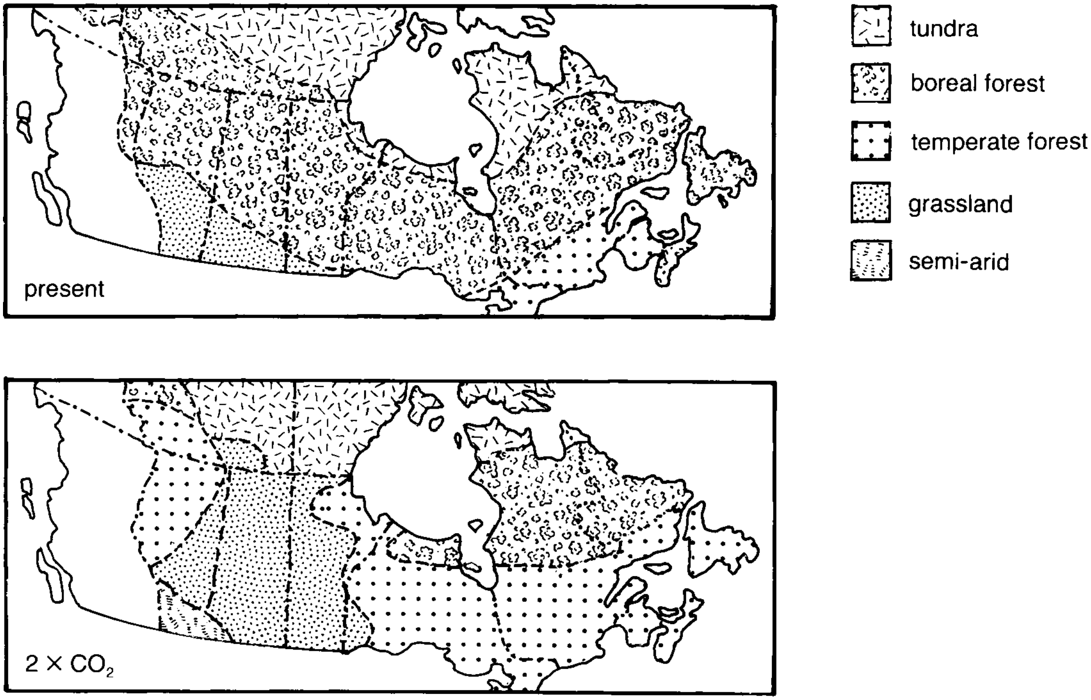
The presence of these other greenhouse gases introduces a number of uncertainties into the predictions of future greenhouse levels. None of them is individually as important as $CO_2$. It has been suggested, however, that their combined influence on the greenhouse effect is already equivalent to half that of $CO_2$ alone (Bolle *et al.* 1986), and by early next century their contribution to global warming could be equal to that of $CO_2$ (Ramanathan *et al.* 1985). Their impact would become increasingly important in the low $CO_2$ emission scenarios envisaged by some investigators. The involvement of the CFCs and $N_2O$ in the depletion of the ozone layer adds a further complication. Attempts to mitigate the effects of these gases on the ozone layer would also impact on the greenhouse effect. Thus, although such gases as $CH_4$, $N_2O$ and the CFCs have received much less attention than $CO_2$ in the past, it is clear that plans developed to deal with global warming must include consideration of all the greenhouse gases, not just $CO_2$ (see Figure 7.10).

## ENVIRONMENTAL AND SOCIO - ECONOMIC IMPACTS OF INCREASING GREENHOUSE GASES

Given the wide range of possibilities presented in the estimates of future greenhouse gas levels and the associated global warming, it is difficult to predict the environmental and socio-economic effects of such developments. However, using a combination of investigative techniques—ranging from laboratory experiments with plants to the creation of computer generated models of the atmosphere and the analysis of past climate anomalies—researchers have produced results which provide a general indication of what the consequences might be in certain key sectors.

The impact of elevated $CO_2$ levels on natural and cultivated vegetation has received considerable attention. Two elements are involved since elevated $CO_2$ has an effect on both photosynthesis and on temperature. Through its participation in photosynthesis, $CO_2$ provides the carbon necessary for proper plant growth, and in laboratory experiments under controlled conditions it has been shown that increased concentrations of the gas enhance growth in most plants. The bulk of the earth's vegetation can be classified into two general groups—$C_3$ and $C_4$—which differ in the biochemistry of their photosynthetic processes. The $C_3$ group makes up about 95 per cent of the earth's biomass, and includes important grain crops such as wheat, rice, and soybeans, while the smaller $C_4$ group is represented by maize, sorghum and millet. Most trees belong to the $C_3$ group. Both $C_3$ and $C_4$ plants react positively to increased levels of $CO_2$, with the former being most responsive (Melillo *et al.* 1990). A doubling of $CO_2$ has increased yields of maize, sorghum, millet and sugar cane by 10 per cent in controlled experiments, and increases of as much as 50 per cent have been achieved with some $C_3$ plants (Environment Canada 1986). The response of natural vegetation or field crops might be less, because of a variety of non-climatic variables, but some trees do seem capable of responding quite dramatically. For example, Sveinbjornsson (1984) has estimated that a doubling of $CO_2$ would double the rate of photosynthesis in the Alaskan paper birch. Chinese experiments also indicate that higher concentrations of $CO_2$—up to 400–700 ppmv—would bring about increases in the trunk weight, diameter and height of nursery stock, as long as appropriate soil and moisture conditions could be maintained (NCGCC 1990). Some investigators consider the present levels of $CO_2$ to be suboptimal for photosynthesis and primary productivity in the majority of terrestrial plants. They suggest, therefore, that the biological effects of enhanced $CO_2$ would likely be beneficial for most plants

*Figure 7.11* Changing vegetation patterns in Canada following a doubling of $CO_2$




*Source:* After Hengeveld (1991)

(Wittwer 1984). There is some concern, however, that the improvement in the growth rates would be accompanied by a reduction in the quality of plant tissue (Melillo *et al.*1990).

The predicted higher temperatures, working through the lengthening and intensification of the growing season, would have an effect on the rates of plant growth and crop yields. The regional distribution of vegetation would change, particularly in high latitudes where the temperature increases are expected to be greatest (Shugart *et al.* 1986). Across the northern regions of Canada, Scandinavia and Russia, the trees of the boreal forest would begin to colonize the tundra, as they have done during warmer spells in the past (Viereck and Van Cleve 1984; Ball 1986), at a rate of about 100 km for every 1°C of warming (Bruce and Hengeveld 1985). The southern limit of the boreal forest would also migrate northwards, under pressure from the species of the hardwood forests and grasslands which would be more suited, to the new conditions. An expansion of the grassland in western Canada would push the southern boundary of the forest north by 250–900 km (Wheaton *et al.* 1989), and ultimately the boreal forest might disappear completely from northern Alberta, Saskatchewan and Manitoba (see Figure 7.11).

The changing nature and distribution of the northern forest biomes would be the clearest indication of prolonged warming. Accompanying these changes, and contributing to them, would be a series of less obvious factors. Rising soil temperatures, for example, would speed up the provision of soil nutrients through the more rapid decay of organic matter, and contribute to improved plant growth (Van Cleve *et al.* 1983).

New or increased disease and insect infestation might also follow the warming, but that might be offset by a decline in existing infestation problems (Melillo *et al.* 1990). With warmer and potentially drier conditions in the forest, an increase in the frequency of forest fires is a distinct possibility. One element in particular that requires study is the rate at which the forests can respond to the warming. If the temperatures change more rapidly than the forests can accommodate them, then the rapid die-off of large numbers of trees would cause disruption to the northern ecosystems for perhaps centuries to come. This in turn would disrupt the patterns of economic activity in the north, and have a significant effect on those countries such as Canada, Sweden, Finland and Russia, where national and regional economies depend very much on the harvesting of softwoods from the boreal forest.

In lower latitudes, where the temperature element is less dominant and changes are expected to be less, the impact of global warming will often be experienced through changes in the amount and distribution of moisture. Soil moisture levels would decline in areas experiencing a Mediterranean-type climate—southern Europe, South Africa, parts of South America and Western Australia—for example, as a result of reduced precipitation and the higher evapotranspiration rates associated with the warming (Mitchell *et al.* 1990; Pittock and Salinger 1991). Although the vegetation in these areas has adapted to seasonal drought, the extension of the dryness into the normally wet winter season would ultimately bring about changes in the composition and distribution of the Mediterranean climate biome. Extra precipitation in monsoon areas, and the increased poleward penetration of the monsoon rains expected to accompany global warming (Pittock and Salinger 1991) would allow the expansion of the tropical and sub-tropical vegetation of areas such as northern Australia. Elsewhere—the Sahel, for example—the impact of the extra precipitation would be offset, perhaps completely, by increased evapotranspiration rates at higher temperatures.

The conditions likely to alter the regional distribution of natural vegetation are also likely to change the nature and extent of cultivated vegetation. A significant expansion of agriculture is to be expected in mid to high latitudes, where the greatest warming will be experienced. In the interior of Alaska, for example, a doubling of $CO_2$ levels would raise temperatures sufficiently to lengthen the growing season by three weeks (Wittwer 1984), which would allow land presently under forage crops, or even uncultivated, to produce food crops such as cabbage, broccoli, carrots and peas. The growing season in Ontario, Canada, would be lengthened by 48 days in the north and 61 in the south. The reduced frost risk at the beginning and end of the growing season would be a major benefit in some areas. By 2050, in New Zealand and the coastal areas of Australia, for example, the frost-free season may be 30–50 days longer than at present (Salinger and Pittock 1991). The greater intensity of the growing season, along with the effects of increased $CO_2$ on photosynthesis, would lead to increased crop yields. In Europe, simulations of the effects of a doubling of $CO_2$ on crops, using grass as a reference, have indicated an average increase in biomass potential of 9 per cent, with regional values ranging from an increase of 36 per cent in Denmark to a decrease of 31 per cent in Greece (Santer 1985). The increase in agricultural output in China is expected to be 2 per cent, brought about by the greater production of rice, maize and cotton at higher latitudes, and a northward shift of 50–100 km in the cultivation of tropical and sub-tropical fruits (NCGCC 1990).

It may not always be possible for agriculturalists to take full advantage of the benefits of global warming, because of the effects on agricultural production of elements either unrelated or only indirectly related to climate change. Warmer climates would allow the northward expansion of cultivation on the Canadian prairies, for example, but the benefits of that would be offset by the inability of the soils in those areas to support anything other than marginal forage crops, which are not profitable under current economic conditions (Arthur 1988). A major problem in China would be an increase in insect pests such as rice and corn borers, rice winged fleas, army worms, aphids and locusts. Dealing with these would raise pest control costs by 1–5 per cent (NCGCC 1990). Few simulations take such variables into account. The model employed by Santer (1985) to predict changes in European biomass potential included no provision for such important elements as insects, disease and additional fertilizers. Until such unknowns can be estimated, the results of this and similar simulations must be treated with caution.

The most serious problem for agriculture is the increasing dryness likely to accompany the rising temperatures in many areas. Reduced precipitation following changes in circulation patterns, plus the increased rates of evapotranspiration caused by higher temperatures, would create severe moisture stress for crops in many areas (Climate Institute 1988b). Less precipitation and higher temperatures in the farmlands of southern Ontario might reduce yields sufficiently to cause losses of as much as $100 million per year (Smit 1987). The areas hardest hit would be the world's grain producing areas, which would become drier than they are now following the global warming (Kellogg 1987). Corn yields would be reduced in the mid-western plains of the United States, and a major increase in the frequency and severity of drought would lead to more frequent crop failures in the wheat growing areas to the north in Canada (Williams *et al.* 1988). The grain belt in Russia and Ukraine, already unable to meet the needs of these nations, would suffer as badly as its North American equivalent (Kellogg 1987).

Such developments would disrupt the pattern of the world's grain trade, which depends heavily on the annual North American surplus. Food supply problems would become serious in Russia, and famine would strike many Third World countries. In the early 1980s, the picture was not considered completely hopeless, however, for rainfall was expected to increase in some tropical areas, and the combination of more rain, higher temperatures and more efficient photosynthesis would lead to increased rice yields of as much as 10 per cent (Gribbin 1981). Predictions for some of the grain growing areas in Australia also indicated increased precipitation and higher temperatures (Kellogg 1987). However, a 1992 study by Martin Parry—a leading analyst of the agricultural implications of global warming—was much more pessimistic. Computer model projections for the middle of the twenty-first century indicated a decline of 15–20 per cent in grain yields in Africa, tropical Latin America and much of India and south-east Asia, leading to major famine in these areas (Pearce 1992d). Such variations are only to be expected. The many elements which together determine the distribution of natural and cultivated vegetation, and the complex interrelationships involved, are imperfectly understood. It is therefore very difficult to depict them accurately in current models. Coupled with the limited ability of most global models to cope with regional scale processes to which ecosystems respond, this ensures that the ultimate changes in natural and cultivated vegetation resulting from global warming must remain speculative.

Most of the agricultural projections note the importance of an adequate water supply if the full benefits of global warming are to be experienced. Beyond that, little work has been done on the impact of an intensified greenhouse effect on water resources. Canadian studies have examined the implications of climate change for future water resources in the Great Lakes—St Lawrence River System (Sanderson 1987), and in northern Quebec (Singh 1988). In Australia, scientists using a high-resolution nested model (see Chapter 2) have been able to simulate the hydrology of the south-eastern part of the continent more accurately than is possible with existing global models. With a resolution about ten times finer that that of the global models, the nested model provides a better representation of those regional factors—surface morphology, for example—known to influence strongly the distribution and intensity of precipitation and run-off. The model has performed favourably in simulating current hydrological events, and with further development it should be able to provide a more accurate representation of regional hydrology following global warming than is currently possible. Beyond such studies, the general lack of attention to the hydrologic cycle following global warming is an important gap in current research.

One aspect of global hydrology which has been considered in some detail is the impact of higher world temperatures on sea level. Warming would cause sea level to rise as a result of the thermal expansion of sea water and the return of additional water to the oceans from melting temperate glaciers. Global mean sea level has already been rising by about 1.5 cm per decade over the past century, and with global warming that rate is likely to accelerate to between 3–10 cm per decade (Hengeveld 1991). The IPCC has estimated that by 2030 sea level will be 18 cm higher than at present, and by 2070 the rise will be 44 cm (Warrick and Oerlemans 1990). Earlier studies indicated that mean sea level might rise by as much as a metre as early as 2050 (Titus 1986), but the IPCC assessment does not foresee a rise of that amount during the next century (Warrick and Oerlemans 1990).

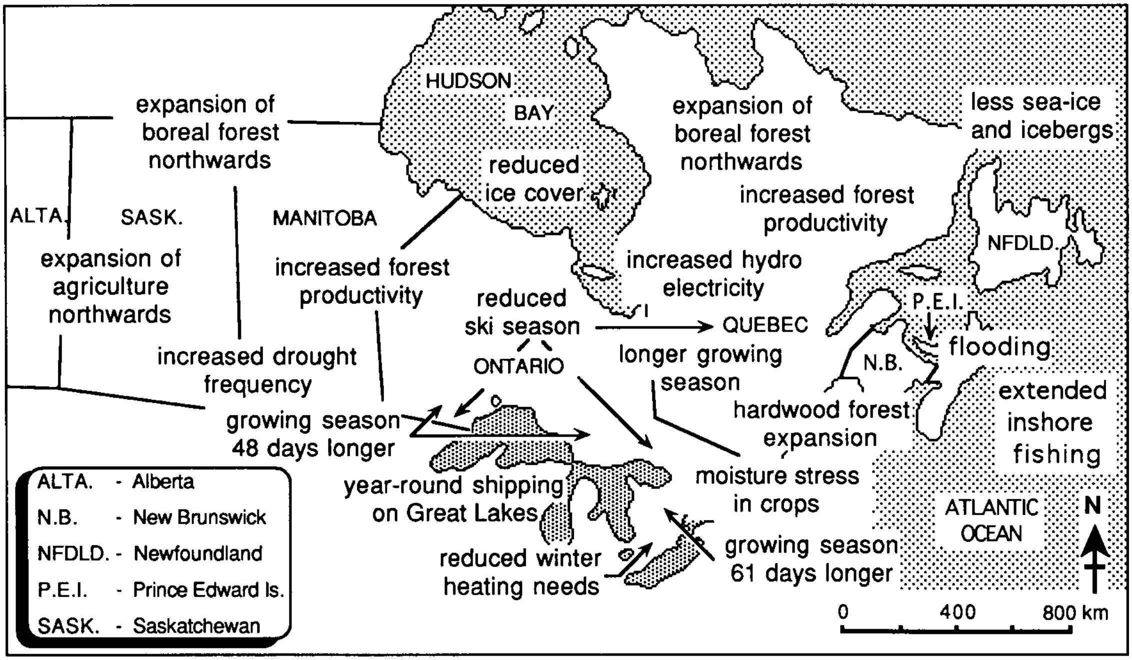
Although such increases are relatively minor compared to past changes in sea level, they would be sufficient to cause serious flooding and erosion in coastal areas. In low lying regions such as the Netherlands already dependent upon major protective works, even a sea level rise of half that postulated would have major consequences (Hekstra 1986). Land close to sea level in Britain—around the Wash, for example—would be similarly vulnerable, and structures like the Thames Flood Barrier might be needed on other British rivers. Environment Canada has commissioned studies of the impact of sea level rises in the Maritime Provinces, which show that flooding events or storm surges would become more frequent and severe, presenting serious problems for sewage and industrial waste facilities, road and rail systems and harbour activities (Martex Ltd. 1987; Stokoe 1988).

A sea level rise of little more than 20 cm would place some 1.1 m hectares in jeopardy along the east coast of China, from the Pearl River in the south to Bohai Bay in the north (NCGCC 1990). In Bangladesh, more than 100,000 hectares would be inundated by a 50 cm rise in sea level (Mackay and Hengeveld 1990), causing the loss of good agricultural land and displacing tens of thousands of people. Some of the island nations in the Pacific and Indian Oceans would face even more serious problems. The highest point on the Maldive Islands in the Indian Ocean, for example, is only 6 m above present sea level (Hengeveld 1991), and the average elevation of the Marshall Islands in the west central Pacific is less than 3 m (Climate Institute 1992a). Both areas are already being threatened by flooding and increased coastal erosion, and if sea level continues to rise they will become uninhabitable.

The impact of even small rises in sea level is increased during high tides or storms, and when the two combine the results can be disastrous. In 1953, for example, high tides and a storm surge in the North Sea led to major flooding in eastern England, Belgium and the Netherlands. Over 2,000 people drowned. At that time, such an event was to be expected no more than once in 150 years. Since then, with rising sea levels, the odds have shortened to once in 35 years, despite the development of better coastal defences (Simons 1992).

Whether storminess would increase or decrease in a warmer world remains a matter of controversy. In mid-latitudes, the storms that develop in the North Atlantic and Pacific and across the southern oceans, are driven by a strong latitudinal temperature gradient. With the rising temperatures projected for higher latitudes, that gradient would be reduced, and mid-latitude storminess might therefore be expected to decline (Houghton *et al.* 1990). It is possible, however, that those storms that do develop will be more intense, fuelled by greater evaporation rates over a warmer ocean, and the consequent increase in the energy flux between ocean and atmosphere.

*Figure 7.12* Environmental and economic changes expected in central and eastern Canada following a doubling of atmospheric $CO_2$ levels




This could lead to an increase in the incidence of the intense low pressure systems that wrought havoc in Britain and western Europe in 1987 and again in 1990 (Simons 1992). Unfortunately, current models are unable to resolve the processes involved in these relatively small scale or regional phenomena, and predictions on storminess in middle latitudes remain inconclusive.

Similarly, climate models are inconsistent in their predictions of the frequency and intensity of tropical storms—cyclones, typhoons and hurricanes—following global warming. These storms only develop over oceans where sea surface temperatures (SSTs) exceed 26–27°C. With global warming, such temperatures would be exceeded more frequently, and over larger areas, than at present, leading to an increase in the number of tropical storms. In the southern hemisphere, with an SST warming of only 2–4°C, tropical cyclones would become 20 per cent more intense and form perhaps 200–400 km further to the south than at present (Salinger and Pittock 1991). Such storms currently move out of the tropics to become intense extratropical depressions, which bring heavy precipitation and strong winds to mid-latitudes. With warming these travelling storms would be expected to move farther north and south, sustained in part by energy transferred from the warmer oceans. Areas such as Australia, New Zealand and the coasts of the north Pacific and north Atlantic would suffer, but some of the island nations of the south Pacific might not survive such a train of events.

Aware of the problems they might face in the future, the nations most likely to be affected came together as the Alliance of Small Island States (AOSIS), and as such were successful in having their situation addressed as part of the UN Framework Convention on Climate Change at Rio in 1992. AOSIS is hoping for the creation of a disaster insurance scheme funded by the developed nations—whom they see as mainly responsible for the climate change that threatens them—which will help in the creation of disaster prevention programmes (Climate Institute 1992b).

Even in those areas not completely inundated, the relationship between sea level and regional hydrology would allow the effects to be felt some distance inland in the form of altered streamflow patterns and groundwater levels. In time, the impact of higher temperatures on the rate of ablation of ice caps and sea ice in polar regions might be sufficient to cause a rise in mean sea level of between 3 and 4 m (Hoffman *et al.* 1983). Should this ever come to pass, most of the world's major ports would not survive without extensive and costly protection.

This disruption of commercial activities by rising sea-level in coastal regions is only one of a series of economic impacts which would accompany global warming. Others range from changes in energy use, particularly for space heating, to the development of entirely new patterns of recreational activity. Because of its northern location, Canada is especially susceptible to such changes, and as a result Environment Canada has invested a great deal of time and effort in viewing the greenhouse effect from a Canadian perspective (see Figure 7.12). The results of the studies, although specific to Canada, may also give an indication of future developments in other northern regions such as Scandinavia and Russia (Kemp 1991).

### Alternative points of view and the problems of GCMs

The global warming scenario, in which a doubling of atmospheric $CO_2$ would cause a temperature increase of 1.3–4.5°C, is widely accepted. This consensus has evolved from the results of many experiments with theoretical climate models which indicate the considerable potential for change in the earth/atmosphere system as concentrations of atmospheric greenhouse gases increase. Even the most sophisticated General Circulation Models (GCMs) cannot represent the working of the atmosphere exactly, however, and the limitations that this imposes on the results have long been a source of criticism. One of the earliest and most vociferous critics of the theoretical modelling approach was Sherwood Idso, who attacked the established view of future global warming through numerous publications (e.g. Idso 1980, 1981, 1982, 1987). He suggested that increasing $CO_2$ levels would produce negligible warming, and might even cause global cooling. His conclusions were based on so-called natural experiments in which he monitored temperature change and radiative heat flow during natural events—such as dust storms, for example. From these he estimated the temperature change produced by a given change in radiation. Since the effects of increasing $CO_2$ levels are felt through the disruption of the radiative heat flow in the atmosphere, it was therefore possible to estimate the temperature change that would be produced by a specific increase in $CO_2$. Initially,

Idso (1980) suggested that the effect of a doubling of atmospheric $CO_2$ would be less than half that estimated from the models. Later he concluded that increasing $CO_2$ levels might actually cause cooling (Idso 1983). Idso received some support for his views (e.g. Gribbin 1982; Wittwer 1984), but for the most part, his ideas were soundly criticized by the modelling community, sometimes in damning terms (NRC 1982, Cess and Potter 1984). Although they initiated an intense—and sometimes acrimonious—debate on the methods of estimating climate change, in the long term Idso's natural experiments did little to slow the growing trend towards the use of GCMs. However, even with the growing sophistication of the models, those who used them were often the first to note their limitations (e.g. Rowntree 1990), and many of the criticisms of the estimated impact of elevated $CO_2$ levels have arisen out of the perceived inadequacies of the models used (Kerr 1989).

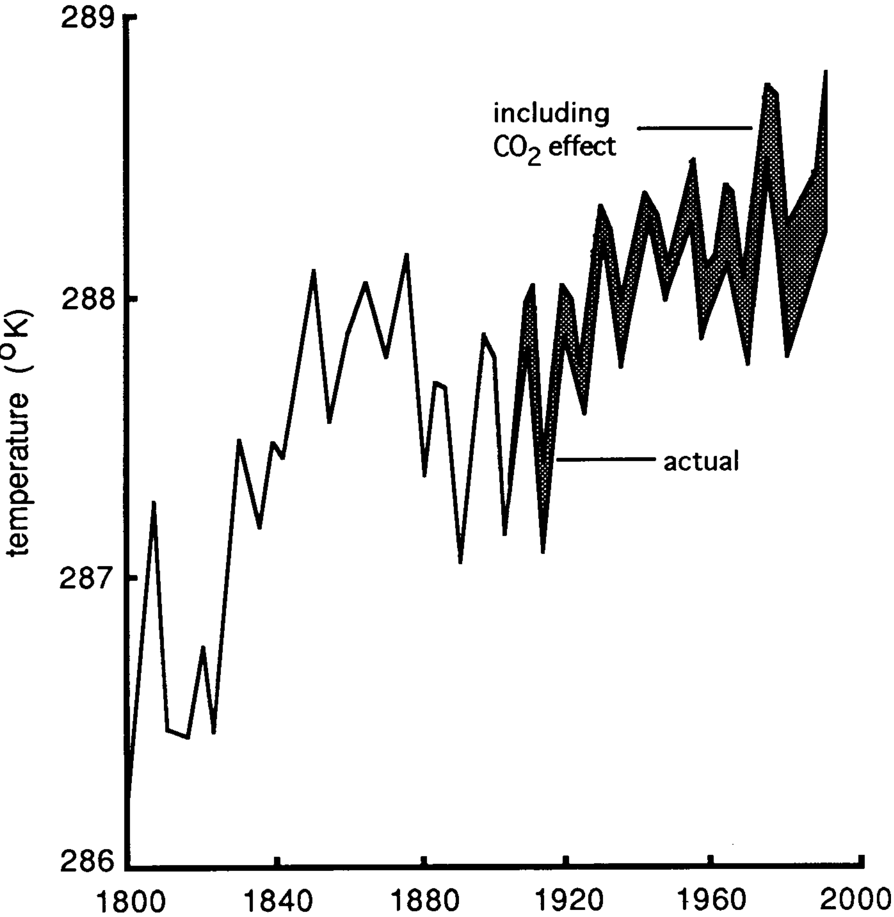
Many of the problems associated with GCMs arise from their inability to deal adequately with elements that are integral to the functioning of the earth/atmosphere system. The roles of clouds and oceans in global warming are poorly understood, for example. The former are difficult to simulate in GCMs, in part because they develop at the regional level, whereas GCMs are global in scale. Parameterization provides only a partial solution (see Chapter 2), and the IPCC supplement has identified the problem of dealing with clouds, and other elements of the atmospheric water budget, as one of the main limitations to a better understanding of climate (Houghton *et al.* 1992).

Oceans create uncertainty in climate models mainly as a result of their thermal characteristics. They have a greater heat capacity than the atmosphere and a built-in thermal inertia which slows their rate of response to any change in the system. Thus, models which involve both atmosphere and ocean have to include some concessions to accommodate these different response rates. In representing the oceans it is not enough to deal only with surface conditions, yet incorporating other elements—such as the deep ocean circulation—is both complex and costly. As a compromise, many coupled ocean/atmosphere climate models include only the upper, well-mixed layer of the oceans. These are the so-called 'slab' models in which the ocean is represented by a layer or slab of water about 70 m deep. While of limited utility in dealing with long-term change, this approach at least allows the seasonal variation in ocean surface temperatures to be represented (Gadd 1992). A more realistic representation of the system would require coupled, deep-ocean/atmosphere models, but their development is constrained by the limited observational data available from the world's oceans and the high demands that such models place on computer capacity and costs. Existing coupled models do provide results consistent with current knowledge of the circulation of the oceans, but they are simplified representations of reality, lacking the detail required to provide simulations that can be accepted with a high level of confidence (Bretherton *et al.* 1990).

GCMs also have difficulty dealing with feedback mechanisms which act to enhance or diminish the thermal response to increasing greenhouse gas levels (Rowntree 1990). Feedbacks are commonly classified as positive or negative, but in the earth/atmosphere system they may be so intimately interwoven that their ultimate climatological impact might be difficult to assess. For example, the higher temperatures associated with an intensified greenhouse effect would bring about more evaporation from the earth's surface. Since water vapour is a very effective greenhouse gas, this would create a positive feedback to augment the initial rise in temperature. With time, however, the rising water vapour would condense, leading to increased cloudiness. The clouds in turn would reduce the amount of solar radiation reaching the surface, and therefore cause a temperature reduction—a negative feedback—which might moderate the initial increase. Such complexities are difficult to unravel in the real world. Their incorporation in climate models is therefore not easy, but the importance of atmospheric water vapour feedback in climate change is well recognized by researchers (Ramanathan *et al.* 1983; Ramanathan 1988), and at least some of the mechanisms involved are represented in most current models.

Feedbacks associated with global warming are present in all sectors of the earth/atmosphere system, and some have the potential to cause major change. The colder northern waters of the world's oceans, for example, act as an important sink for $CO_2$, but their ability to absorb the gas decreases as temperatures rise (Bolin 1986). With global warming expected to be significant in high latitudes there would be a reduction in the ability of the oceans to act as a sink. Instead of being absorbed by the oceans, $CO_2$ would remain in the atmosphere, thereby adding to the greenhouse effect. On land the feedbacks often work through soil and vegetation. Increased organic decay in soils at higher temperatures would release additional greenhouse gases—such as $CO_2$ and $CH_4$—into the atmosphere, producing a positive feedback. This may be particularly effective in higher latitudes where the tundra, currently a sink for $CO_2$, would begin to release the gas into the atmosphere in response to rising temperatures

*Figure 7.13* Changing global annual surface temperature




*Source:* After Schneider and Mass (1975)
*Note:* The lower line between 1900 and 1990 indicates actual change, whereas the upper line indicates the estimated temperature if the enhanced greenhouse effect is included. The temperature expressed in K is equivalent to temperature in degrees Celsius plus 273.15°C. It is possible that the difference has been caused by the cooling effects of increased atmospheric turbidity, which have prevented the full impact of the enhanced greenhouse effect from being realized

(Webb and Overpeck 1993). The additional flux of carbon from terrestrial storage might add as much as 200 billion tonnes of carbon to the atmosphere in the next century (Smith and Shugart 1993). In contrast, higher temperatures and more efficient photosynthesis in low and middle latitudes would initiate a negative feedback in which increased vegetation growth would cause more $CO_2$ to be recycled and stored (Webb and Overpeck 1993).

Feedback mechanisms are incorporated in some form in most GCMs. However, the number and complexity of the feedbacks included, varies from model to model, and current modelling techniques continue to have difficulty dealing with them. Such constraints in the existing models must be recognized, and appropriate allowances made when predictions of global warming are used.

A basic concern among some researchers is the concentration on one variable—greenhouse gas levels—which has allowed the role of other elements in the system to be ignored. It is well-known that the earth's climate is not static, but has varied over the years (see e.g. Lamb 1977). Some of the variations have been major, such as the Ice Ages, whereas others have only been detectable through detailed instrumental analysis. Some have lasted for centuries, some only for a few years. While it is relatively easy to establish that climatic change has taken place, it is quite another matter to identify the causes. There are a number of elements considered likely to contribute to climatic change, however.

Since the earth/atmosphere system receives the bulk of its energy from the sun, any variation in the output of solar radiation has the potential to cause the climatic change. The links between sunspot cycles and changes in weather and climate have long been explored by climatologists (see e.g. Lamb 1977), and there are researchers who claim that solar variability has a greater impact on global climate than the greenhouse effect. For example, a report prepared for the Marshall Institute—a think-tank in Washington DC—suggested that reduced solar output in the near future might offset current global warming sufficiently to initiate a new Ice Age. The IPCC assessment considered this unlikely, however, pointing out that the estimated solar changes are so small that they would be overwhelmed by the enhanced greenhouse effect (Shine *et al.* 1990). Even if the solar energy output remains the same, changes in earth/sun relationships may alter the amount of radiation intercepted by the earth. Variations in the shape of the earth's orbit, or the tilt of its axis, for example, have been implicated in the development of the Quaternary glaciations (Pisias and Imbrie 1986).

The present intensification of the greenhouse effect is directly linked to the anthropogenic production of $CO_2$; in the past, however $CO_2$ levels have increased with no human contribution whatsoever. During the Cretaceous period, millions of years before the Industrial Revolution, $CO_2$ concentrations were much higher than they are today (Schneider 1987). Other changes in the composition and circulation of the atmosphere have to be considered also. The impact of increased atmospheric turbidity is not clear. It may add to the general warming of the atmosphere (Bach 1976) but it has also been used to explain global cooling between 1940 and 1960, at a time when $CO_2$ levels continued to rise (see Figure 7.13). Although this cooling is usually acknowledged as a problem by researchers, it has not yet been adequately explained (Wigley *et al.* 1986). More recently, the eruption of Mount Pinatubo in mid-1991 caused cooling which appears to have been sufficient to reverse the global warming of the 1980s and early 1990s. There is also some evidence that the turbidity increase caused by the eruption may have contributed to regional warming (see Chapter 5).

Thus there are many elements in the earth/atmosphere system capable of producing measurable climate change. Given their past contribution to change, it seems unlikely that they will now remain quiescent while anthropogenic $CO_2$ provides its input. Despite this, they have been ignored by most researchers or are considered of minor importance compared to the potential impact of the greenhouse gases (Roberts 1989).

Research into global warming is continuing at a high level, and it is possible that a better understanding of its interaction with other elements in the earth/atmosphere system will emerge to resolve some of the existing uncertainties. If not, society will have to deal with the future environmental changes in much the same way as it has done in the past—by reacting to them after they have happened.

## SUMMARY

The earth's greenhouse effect has been intensifying since the latter part of the nineteenth century, largely as a result of human activities. The increased use of fossil fuels has raised the level of $CO_2$ in the atmosphere, and the destruction of natural vegetation has prevented the environment from restoring the balance. Levels of other greenhouse gases—including $CH_4$, $N_2O$ and the CFCs—have also been rising and the net result has been a gradual global warming. If present trends continue, a rise in mean global temperatures of 1.5°C–4.5°C is projected by the early part of the twenty-first century. These values are not accepted by all scientists studying the situation, but there is enough evidence to suggest that a major global climate change is in progress. The ultimate magnitude of the change is uncertain, but it has the potential to cause large-scale alterations to the natural environment and to global socio-economic and political systems. For these reasons, the search for a better understanding of the situation is being given priority, both nationally and internationally. There has always been a high degree of cooperation among the world's environmental scientists, but it seems likely that such cooperation will have to extend to other physical scientists, social scientists and decision-makers, if society is to be in the best possible position to cope with what could well be the greatest global temperature rise in history.

## SUGGESTIONS FOR FURTHER READING

Flavin, C. (1989) *Slowing Global Warming: A Worldwide Strategy*, (Worldwatch Paper 91) Washington DC: Worldwatch Institute.

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (1990) *Climate Change: The IPCC Scientific Assessment*, Cambridge: Cambridge University Press.

Houghton, J.T., Callender, B.A. and Varney, S.K. (1992) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge: Cambridge University Press.

Rosen, L. and Glasser, R. (1992) *Climate Change and Energy Policy*, New York: American Institute of Physics.

# 8

# Present problems, future prospects

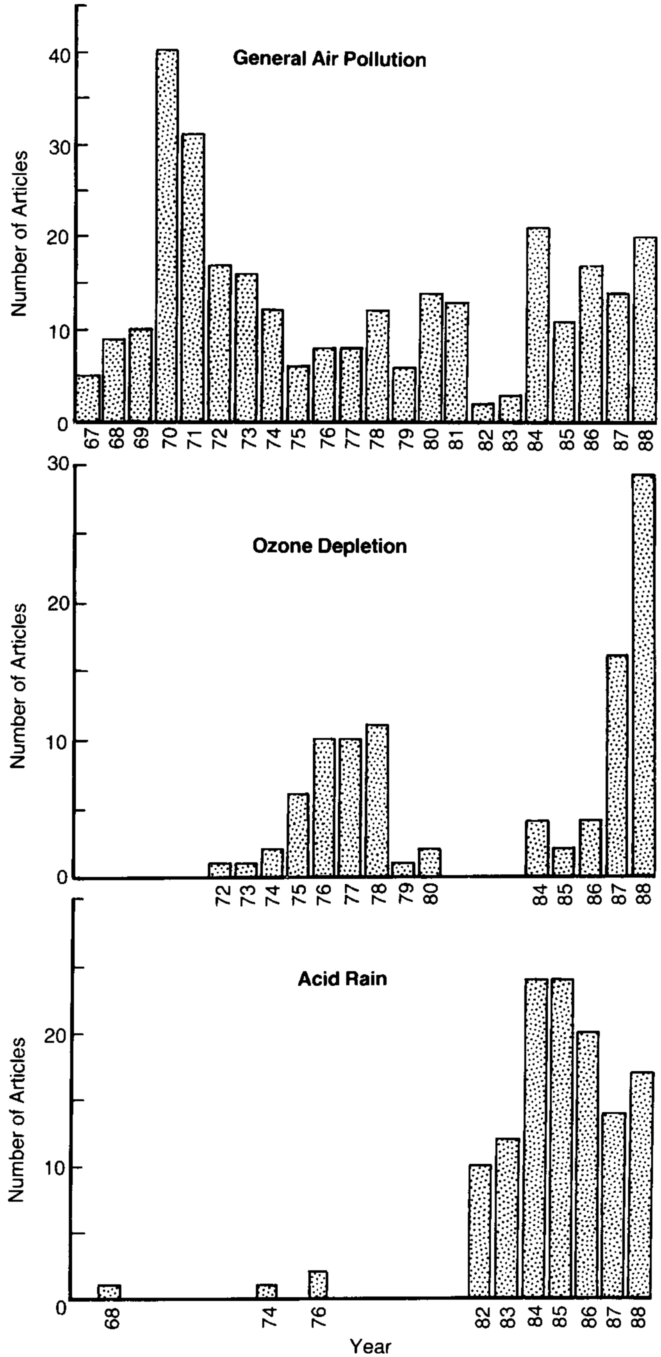
Public interest in the global environmental issues described in the preceding chapters has waxed and waned over the past decade (see Figure 8.1). At present, ozone depletion and global warming elicit a high level of concern, whereas drought and desertification, acid rain and atmospheric turbidity have a much lower profile than they once had. With the break-up of the Soviet Union, the re-alignment of eastern Europe and the end of the 'Cold War', nuclear winter is no longer considered a serious threat by most observers. This situation reflects current perceptions of the seriousness of particular problems. Perceptions can change, however. Since few members of the general public are in a position to read the original scientific reports which address the issues, they must depend upon an intermediary to satisfy their interest. In modern society this interpretive role has been filled by the media, and public perception of the issues is formed to a large extent by their rendition of research results. Without them, the general level of understanding of the problems would be much lower than it is, but, as a group, the media have also been accused of sensationalizing and misinterpreting the facts supplied by the scientific community. There can be no doubt that some of the accusations are valid, but scientists too may be partly to blame for allowing conclusions to be presented as firm, before all of the facts are in. Such was the case with the initial investigation of nuclear winter, and also with the discovery of the hole in the ozone layer above the Antarctic in the mid-1980s. Given the scale and complexity of current environmental issues, problems of interpretation and dissemination are inevitable. They must not be allowed to divert attention from the main task, however, which is the search for solutions to the major issues.

## CURRENT STATE OF THE ISSUES

### Atmospheric turbidity

One of the first environmental issues to be considered in a global context was the rising level of atmospheric turbidity, which was the centre of concern in the mid-1970s. It linked air pollution with the cooling of the earth. Cooling had been taking place since the 1940s, and some writers saw the world descending into a new Ice Age. It was clear a decade later that the cooling had reversed, and atmospheric turbidity began to receive less attention. Evidence also began to appear indicating that increased atmospheric turbidity might actually contribute to atmospheric warming. Currently, it raises little concern among the general public, except under exceptional circumstances such as those created by the Kuwaiti oil fires and the eruption of Mount Pinatubo. Both of these events initiated cooling and serve as a reminder that exceptional conditions capable of augmenting turbidity cannot be ignored. Although air pollution may be serious in specific areas, the human contribution to atmospheric turbidity is generally smaller, and the overall impact much less than that from natural sources—the cooling associated with the oil fires in Kuwait, for example, remained local, whereas that caused by Mount Pinatubo was global. Whether or not

*Figure 8.1* Changing levels of interest in environmental problems, as reflected in coverage in *The Times* newspaper between 1967 and 1988




*Source:* From Park (1991)

that means that anthropogenic contributions to atmospheric turbidity are relatively unimportant remains to be seen, and scientists interested in the impact of human activities on the atmosphere continue to search for an answer.

### Nuclear winter

Interest in nuclear winter has also waned from a peak reached between 1983 and 1985. Intensive investigation of the issue from 1983 on produced increasing evidence that the climatic impact of nuclear war had been overestimated in the original study. The downgrading of the estimates in the scientific and academic community was inevitably accompanied by a general decline in the level of public interest in the topic, and despite a new examination of the theory by the original investigators (Turco *et al.* 1990)—which tends to reaffirm the basic findings of the original work—there has been no revival of interest.

As a result of recent political developments, nuclear conflict does seem less likely, and the issue of nuclear winter is regarded as irrelevant by some. Certainly, large scale nuclear war between the NATO and Warsaw Pact powers is no longer a consideration. The events which reduced the likelihood of superpower nuclear conflict did nothing to reduce local and regional tensions, however, and in some cases may even have exacerbated them. With the dissolution of the USSR into a number of separate states, for example, central control over nuclear devices has been lost, and the possibility of these weapons being used in local conflicts cannot be ruled out. However, in early 1994, Ukraine agreed to the complete destruction or removal of all the nuclear weapons it had inherited from the former USSR. In the Middle East, Israel may already have a nuclear capability, while other nations in the region may be working towards that end. Both India and Pakistan also have nuclear ambitions. Elsewhere in Asia, North Korea has shown a distinct reluctance to abstain from further development of nuclear weapons. The availability of nuclear weapon scientists, thrown out of work by the new political reality, which has reduced the military requirements of the superpowers, is also a concern. Their ability to aid smaller nations—particularly in politically unstable parts of the world—to acquire or build nuclear devices could lead to the proliferation of such weapons. Although conflicts in these regions would not match the size or severity of nuclear exchange upon which the original nuclear winter hypothesis was based, they would certainly have significant local and regional environmental impacts, which in some cases could have global consequences.

### Drought, famine and desertification

Drought, famine and desertification are related problems of long standing in many parts of the world. The disastrous droughts in the Sahel in the 1960s and 1970s, for example, were only the most recent in a series which can be traced back several centuries. The earlier droughts, and their accompanying famines, passed mostly unnoticed outside the areas immediately affected. In contrast, modern droughts have been characterized by a high level of concern, particularly in the developed nations of the northern hemisphere. Concern is often media-driven, rising rapidly, but falling just as quickly when the drought breaks or the initial benefits of food and medical aid become apparent. When the rains returned to the Sahel in the late 1970s, interest in the problems of the area declined, although the improvements were little more than minimal. Similarly, the concern raised by television reports of drought and famine in Ethiopia in the mid-1980s peaked at a very high level in 1985 only to decline again within the year. Such fluctuations give a false impression of the problem. Drought and famine are endemic in many parts of the world, and do not go away when the interest of the developed nations declines. In some areas, the return of the rains does bring periodic relief and the land produces a crop. Where the relief is infrequent or short-lived, the desert advances inexorably into previously habitable land. This is desertification in its most elemental form. Accelerated by human interference, it has become the most serious environmental problem facing some of the countries of the earth's arid zones. Climatologists, agronomists, foresters and scientists from a number of United Nations organizations have been wrestling with it for nearly forty years, yet even now it receives less public recognition than the drought and famine with which it is associated. Despite this lengthy investigation, attempts at the prevention and reversal of desertification have met with only limited success. In part, this appears to be the result of misinterpretation of the evidence, and all aspects of the problem—from identification, through causes, to response—are currently undergoing rigorous reassessment. Like most environmental issues, desertification is not just a physical problem. It has socio-economic and political aspects—ranging from the depressed economies of many Third World nations to the civil strife in countries like Ethiopia and Somalia—which complicate the search for appropriate solutions.

Public interest in drought, famine and desertification will continue to fluctuate. Heightened concern, followed by increased financial, nutritional and food aid, may help to alleviate some of the immediate effects of the problems, but it is the steady, less volatile interest of the scientific community which has the potential to bring about longer-term relief.

## Acid rain

The study of acid rain has declined remarkably since the early 1980s, when it was viewed by many as the major environmental problem facing the northern hemisphere. This decline has led one writer to wonder, 'Whatever happened to acid rain?' (Pearce 1990). It certainly has not disappeared, but it is one environmental issue in which abatement programmes have met with some success. Sulphur dioxide levels continue to decline, the rain in many areas is measurably less acid than it was a decade ago, and the transboundary disputes which absorbed large amounts of time, energy and money in the 1980s, have been resolved. There are indications that lakes and forests are showing some signs of recovery in the most vulnerable areas of North America and Europe, although this is still a matter of some dispute.

Developments such as these have created the perception that the acid rain problem is being solved. Interest has declined, and the research funds available have been diverted to causes—such as ozone depletion and global warming—that now appear more relevant. Although acid rain is arguably a less serious problem than it once was, it has not been solved. It has changed in nature and geographical extent, however. In the developed nations, $NO_X$ is gradually making a larger contribution to acidity as levels of $SO_2$ decline. In less developed areas, from eastern Europe to China and parts of the southern hemisphere, the full impact of acid rain may still be in the future, and the research activities currently winding down may have to be revived to deal with it.

## Ozone depletion and global warming

Ozone depletion and global warming currently enjoy a much higher profile than the other environmental issues, both in the media and in the scientific community. They are the focus of major research efforts costing millions of dollars aimed at deciphering the causes and effects of the problems so that solutions can be identified. The intensity of the research effort has ensured some success, but in many cases the search for information has done little more than confirm the complexity of the earth/atmosphere system. Interest in the topics has been developed and maintained through a continuing series of high level international conferences, some of which concentrate on the technical aspects of the problems, while others involve policy development and decision-making. These are complemented by national and regional conferences dealing with specific aspects of the problems.

Progress in the development of the topics has not been even. Consideration of ozone depletion has already reached the decision-making stage, whereas in the study of global warming the technical aspects of the issue—such as the establishment of the nature, extent and timing of the warming—continue to receive much of the attention. This may reflect the relative complexity of the two issues. Controlling CFCs is relatively easy, for example, because their uses are limited, the small number of producers can be easily identified and production can be monitored. Substitutes for many CFCs have been developed quite easily. In contrast, greenhouse gas production is widespread, with a mixture of natural and anthropogenic sources which are difficult to monitor with any accuracy. The size and complexity of the problem is such that there has been little development of replacements for the products and processes releasing greenhouse gases. The greater progress in dealing with thinning ozone is also an indication of the different ways in which the problems are perceived. Of the two, ozone depletion is usually seen as having the most serious consequences. The discovery of the Antarctic ozone hole was followed closely by the initiation of international efforts to save the ozone layer, which gained momentum with every new report of ozone depletion.

The Vienna Convention on the Protection of the Ozone Layer, which emerged from a 1985 conference, was followed in 1987 by the Montreal Protocol. Signatories to the Protocol agreed to reduce production of CFCs by 50 per cent (of 1986 values) by 2000. The concluding statement of the World Conference on the Changing Atmosphere, held in Toronto, Canada in mid-1988, also included reference to CFCs. It called for them to be phased out by the year 2000, and, later that year, delegates at the World Conference on Climate and Development in Hamburg, Germany recommended a global ban on the production and use of CFCs by 1995. In March 1989, the members of the European Community agreed to eliminate production and use of ozone-destroying chemicals by the end of the century. The US government endorsed the effort, but stressed the importance of finding safe substitutes for CFCs. In Australia in 1989, the government passed the Ozone Protection Act which, with supplementary regulations, was aimed at eliminating CFC and halon use by 1994. At about the same time, major, government-sponsored conferences in London and Paris provided international support for a worldwide ban on CFCs and other environmentally harmful chemicals. Subsequent meetings have confirmed the willingness of the nations of the world to deal with the issue, and the second half of the 1990s will see the progressive elimination of CFCs and other ozone-destroying compounds. There is already evidence of a decrease in the growth rate of atmospheric halons (Butler *et al.* 1992) and certain CFCs (Elkins *et al.* 1993). The growth of CFC-11 and CFC-12 is slowing, for example, and if this continues as expected, the volume of these gases in the atmosphere will reach a peak by the end of the century, and then begin to decline. Even with such developments, the ozone layer will take time to recover, and levels of UV-B rays reaching the earth's surface will remain high. In October 1993, for example, the US National Oceanic and Atmospheric Administration announced that the amount of ozone in the atmosphere above Antarctica had reached a record low, being virtually absent between 13.5 km and 18 km above the surface. Announcements such as this apparently confirming the progressive thinning of the ozone, have prompted government agencies from as far apart as Australia and Canada to issue warnings about exposure to excess ultraviolet radiation, and these warnings are currently among the most obvious manifestations of the ozone problem.

Like ozone depletion, global warming has been the subject of a large number of conferences and workshops—from Villach in 1985, where the original investigative framework was set up, to Rio in 1992, where it was considered as a major element in the broader study of global change. The net effect has been the accumulation of a considerable body of knowledge on all aspects of global warming, and a recently published annotated bibliography lists several hundred publications on the topic (Handel and Risbey

1992). Much of the material is complex, written in the scientific jargon of research reports, but, perhaps more than any of the other issues, the greenhouse effect has been treated by the media in such a way as to stimulate public interest in the problem. Government organizations have also published the evidence from the research reports in a simplified form for media use and public consumption. The Climate Change Digests of the Canadian Atmospheric Environment Service are a good example of this approach. In addition, private, non-profit organizations—such as the Climate Institute in the United States—have been formed to advance public understanding of the global warming produced by the enhanced greenhouse effect.

The success of these endeavours is difficult to measure, as yet, but the public approach is becoming more common. It reflects the general consensus in the scientific community that solutions to current large-scale environmental problems can only be implemented successfully if they have a high level of public support, and that such support is most likely to come from a public kept well-informed about the nature and extent of the problems. As the investigation of global warming enters the decision-making phase, and solutions involving such elements as tax increases and lifestyle changes are proposed, maintaining that public support will become increasingly important.

## SOLUTIONS

Although there may be individuals and groups who for various reasons are willing to continue with the 'do nothing' or 'business-as-usual' approaches to current global environmental problems, they are a minority, and the urgent need to provide solutions is widely accepted. Given the complexity of the problems being addressed, it is not surprising that there is no one approach that satisfies all needs. Most of the options currently being considered involve either adaptation or prevention, and sometimes a combination of the two.

Adaptation in its simplest form is already part of the earth/atmosphere system, represented by the adjustments required to maintain equilibrium among the various elements in the environment. As part of the environment, human beings have always had the ability to adapt to changing conditions, and in many cases society has been shaped by such adaptation. Can society continue to adjust in the face of the major environmental changes currently taking place? In the short-term the answer is a qualified yes. Adjustment is already under way, and takes many forms. The abandonment of drought-stricken land is one form, for example, as is the addition of lime to acidified lakes. Many individual lifestyle changes—such as wearing a hat, spending less time in the sun or using sunscreen lotion to reduce the impact of higher UV-B levels—are also adjustments to a changing environment. This type of approach may be necessary until appropriate preventative measures are developed, or the full effects of the solutions can work their way through the system.

Adaptation often appears attractive because in the short-term it is a relatively simple and low-cost approach. With time and continuing environmental change, however, the cost of adaptation may eventually exceed the costs of providing solutions. In theory, adaptation and the development of preventative measures should take place in phase so that solutions can be in place before the cost-effectiveness of adaptation is lost. In reality, adaptation is a reactive approach involving little planning or consideration of such elements as timing and cost-effectiveness. Thus the impact of adaptive policies is difficult to predict. However, considering the magnitude of current environmental problems, it seems likely that adaptation can only be a temporary measure. Ultimately, the cumulative effects of the changes will surpass the ability of society to adjust, and solutions will have to be found.

As research into global change continues, it becomes increasingly clear that the only way to ensure that environmental problems will not become progressively worse is to reduce and ultimately halt the processes that cause them. When considered qualitatively, in the academic isolation of the lecture hall or the comfort of an armchair, it appears that all of the current global environmental problems can be solved in that way. They share the same overall cause—human interference in the environment—and specific causes are common to several of the issues. Acid rain, increased atmospheric turbidity, the intensification of the greenhouse effect and ozone depletion could all be reduced with the exercise of greater control over anthropogenic emission of dust, smoke and gases. Those problems which could not be solved completely might have their effects mitigated. It is unlikely, for example, that humankind will ever be able to prevent or control drought, but, through the management of human activities in areas prone to drought, problems of famine and desertification might be alleviated.

The technology exists to tackle most if not all of these problems, but the gap between theory and practice is immense, perhaps insurmountable. It is maintained, in large part, by a combination of political intransigence and the financial constraints under which government and non-government organizations are forced to work. Much of the difficulty arises out of the socio-economic and political consequences of the required changes, which are perceived by some to be even more detrimental to society than the continued existence of the problem. In short, the disease is considered less damaging than the cure. For example, a substantive diminution of acid rain could be accomplished by restricting the use of sulphur-rich, bituminous coal, but it would have the effect of placing in jeopardy the economic viability of the areas producing that commodity. The economic, social and political impact of the closure of dozens of mines, accompanied by thousands of redundancies, may be seen as much more serious than the death of even several hundred lakes. Such concerns continue to influence the methods adopted to control acid rain. Rather than replacing the sulphur-rich coal with a low-sulphur alternative, the problem has been dealt with at the post-combustion stage by the introduction of scrubbers.

Socio-economic and political considerations also limit some of the solutions that might be applied to drought and famine. That problem could be approached by letting nature take its course, as was the norm in the not too distant past. It can be argued that the present system of providing food aid, and drilling wells in areas suffering from famine and drought is the easiest way to ensure that the problems will continue well into the future. Cutting back on aid, or removing it completely, would lead to largescale starvation and death, but it would also reduce stress on the environment, and allow the restoration of some form of equilibrium to the system. Current moral and ethical attitudes would presumably prevent the adoption of such a policy, and even the suggestion that it be considered would have far-reaching political implications.

Energy consumption is an element common to many environmental problems, and its treatment illustrates quite well some of the difficulties faced in the search for solutions. The reassessment of energy sources, leading eventually to a reduction in fossil fuel use is seen by many to provide the most likely solution to the problems of atmospheric turbidity, acid rain and global warming. It is particularly attractive because it is a broad-spectrum solution, which does not require separate technology to be developed for each issue. Improved energy efficiency, for example, would have a wide-ranging impact. It would reduce the output of $CO_2$ and $CH_4$, the main greenhouse gases; it would bring about a decline in atmospheric acidity by reducing emissions of $SO_2$ and $NO_x$; it would create a cleaner and clearer atmosphere by reducing the release of particulate matter. All of these could be achieved without additional technological developments. With cooperation among the developed and developing nations it is technically possible to lower atmospheric $CO_2$ to 1976 levels through improved efficiency (Green 1992). In practical terms this is an unlikely achievement, however. With all of the uncertainties inherent in the global warming predictions, the developed nations might be reluctant to implement the necessary measures because of the initial costs involved, and developing nations—such as China—which see their future development tied to fossil fuels might be unwilling to make what they see as a major sacrifice. Attempts to improve energy efficiency would be accompanied by widespread economic impacts. Although efficiency is usually associated with lower costs, start-up costs would have to be taken into account. Supply and demand patterns would change. Greater efficiency would cause the demand for fuels to fall, which in turn would bring about a decline in prices. Under these circumstances, nations or groups of nations such as OPEC, economically dependent on fossil fuel production would be reluctant to participate in such a scheme.

Cooperation can be encouraged, particularly at the national level, through fiscal measures such as taxation. A carbon tax, paid on fuel consumption has been suggested as a means of reducing fossil fuel use, for example. Although most often proposed as a scheme to slow global warming by slowing down $CO_2$ emissions, it would have an impact on other issues also. It would be relatively easy to set up and administer, and the resulting higher fuel prices would in theory lead to improved energy efficiency. The revenue generated by the tax could be used to offset existing environmental damage created by fossil fuel use, or invested in research aimed at finding solutions to environmental problems.

The simplicity of the carbon tax concept makes it attractive, but it is not without its drawbacks. All tax increases have political consequences, and in a world dependent upon readily available and relatively cheap energy the imposition of a carbon tax would have major socio-economic implications. High cost energy producers would suffer most. Coal and oil producers in North America and Europe would experience a greater financial impact than the oil states of the Middle East, for example. If the tax was graduated according to the polluting potential of the fuel, coal—with its emissions of $CO_2$, $SO_2$ and particulate matter—would be taxed at a higher rate than oil or natural gas. The actual tax levy would vary according to $CO_2$ emission targets and the timeframe proposed. Estimates range from a tax of $20 per tonne of carbon to maintain $CO_2$ emissions at 1990 levels, to $250–275 per tonne to reduce $CO_2$ emissions by 70 per cent from the current estimate for the mid-twenty-first century (Green 1992). None of this would be achieved without international cooperation, and ultimately it would lead to changes in the composition and geographical distribution of the energy industry. The overall higher cost of energy might retard technological development, particularly in the developing nations, and it might be necessary to vary the taxes, not just by commodity but also by source so that the Third World would bear less of the burden. Thus attractive as a carbon tax might appear at first sight, its implementation is not without some obvious and serious economic and political constraints.

Neither improved energy efficiency nor the imposition of an energy tax will halt the impact of fossil fuel use on the environment. At best they can reduce emissions of gases and particulate matter to manageable levels. All of these pollutants are eventually removed from the system by natural recycling processes, but emission levels are now so high that the recycling processes cannot keep up. If they could be rejuvenated, perhaps they could contribute to the solution, or at least the amelioration of certain environmental problems. Such an approach has been proposed to counteract global warming by using the natural ability of plants to remove $CO_2$ from the atmosphere during photosynthesis. It would involve the reforestation of large tracts of land so that carbon could be removed from the atmosphere, and sequestered or stored in the growing vegetation. In Canadian studies, it has been estimated that after taking such factors as land availability, soil conditions and climate into consideration, the maximum possible increase in carbon sequestration would be only 9–10 per cent, at a cost of $6–23 per tonne of carbon stored (Van Kooten *et al.* 1992). To absorb all of the 5 billion tonnes of carbon emitted into the atmosphere annually would require the planting of 1.3–1.7 billion acres of new forest every year, backed up by efficient harvesting and replanting schemes. Clearly this is impossible, and current estimates based on moderate cost-effectiveness suggest that no more than 4–5 per cent of total carbon emissions could be sequestered in this way (Green 1992).

Together, these schemes—improved energy efficiency, carbon taxation and afforestation—would indeed lessen the impact of fossil fuels on the environment, but no major improvement is likely until society's dependence on carbonbased fuels is much reduced. Alternative sources such as the sun, the wind, the sea and the biosphere, cannot supply energy in the amounts and at the rate demanded. The other potential alternative—nuclear fission—has been so discredited by recent events that it cannot be given serious consideration until problems of operational safety and radioactive waste disposal have been resolved. Thus, although developments in the energy sector have the potential to ameliorate a number of existing global environmental issues, major improvements are unlikely under current technological, socio-economic and political conditions.

It is increasingly apparent that solutions to the global environmental problems presently facing society must be economically, socially and politically acceptable. They must be more. Current global problems are multifaceted, therefore the solutions must be multifaceted. They must consider societal and environmental consequences equally, rather than emphasizing the former, as is commonly done at present.

The environment suffers because of the time scales followed by modern society. Politicians, for example, tend to deal in short-term causes, effects and solutions, living as they do from election to election. Many environmental problems do not fit readily into such a framework. Rapid, sometimes catastrophic change is an element in the environment, but, more often than not, change is accomplished through the cumulative effects of relatively minor variations over a long period of time. As a result, potentially important changes may not be recognized, or, if they are, they are ignored because of their seeming insignificance. Even when attempts are made to deal with such changes, the results may only become apparent after a considerable period of time. In the case of ozone depletion, for example, it will take several decades following the complete abolition of CFCs before ozone levels return to their normal range. In politics, where immediate and obvious solutions tend to be the order of the day, such a time lag is often considered politically unacceptable, and no action is taken.

Despite this, concern for environmental change has been growing among politicians and government bodies. They have made funds available for the investigation of global problems, and encouraged the dissemination of the research results through conferences and publications. The next stage in the process must be the implementation of the recommendations contained in the research reports. That is proving to be difficult, however, since it requires a long-range planning strategy, and modern planning policy is designed to provide solutions to short-term problems. Environmental impact procedures, for example, seek to integrate the environmental and socio-economic considerations arising from the development of a specific project and mitigate their effects at the outset. It is assumed that the decisions made at that time will minimize environmental impact throughout the life of the project, but there is already evidence that environmental change is accelerating so rapidly that this approach is now inappropriate. Current environmental problems require long-range planning extending several decades into the future, and responsive to change, if they are to be solved. Planners and policy-makers have not yet adjusted to that requirement. For example, reforestation is going ahead on the assumption that current climatic conditions will prevail during the life-span of the trees, yet in the next 50 years the intensification of the greenhouse effect is likely to cause climate to change in the areas being planted. Irrigation projects and hydro-electric schemes costing millions of dollars are being developed with no thought to the impact of current global problems on precipitation patterns several decades from now. Coastal and waterfront property is being developed as if the rise in sealevel, projected to accompany global warming, is of no consequence. Few of the long-range plans necessary to deal with the problems have been put in place, and there have been few important governmental or industrial decisions which have paid more than lip-service to the recommendations of the research scientists.

The implementation of measures to alleviate the effects of global environmental disruption is further complicated by the scale of the problems. Most will require international cooperation if they are to be controlled successfully. The major conferences which have addressed such issues as acid rain, ozone depletion and the greenhouse effect have been international in scope and have included agreements in principal on the measures required to reduce their impact. Such agreements are important, but they provide no guarantee that the situation will improve. Since they require ratification by individual nations, delays in their implementation are common. One year after the signing of the Montreal Protocol on the depletion of the ozone layer, only seven of the original thirty-seven signatories had ratified the treaty. Even when there is complete ratification, the problem of enforcement remains, and the possibility always exists that the worst offenders may refuse to become involved. For example, Britain and the United States declined membership in the '30 per cent club' when it was formed in 1979 to combat rising levels of acid emissions. Both were major contributors to acid rain, and many environmentalists felt that their lack of cooperation would be disastrous. It was only in the mid-1980s that Britain began to accept some responsibility for downstream acid rain damage, and began slowly to reduce acid gas emissions. It took even longer in North America—more than a decade—before the United States instituted pollution abatement measures that would reduce the export of acid rain north into Canada. Continued high levels of acid gas emissions during these lost years simply added to environmental deterioration, and retarded the necessary clean-up and recovery.

Similar problems arise with drought, famine and desertification. These were originally local issues in the Third World, which became global when the developed nations began to provide relief from drought and famine, and sought to combat desertification. Some success has been achieved against drought and famine, usually by employing the developed world's advanced technology and long-established supply and transport systems. Desertification remains rampant in many areas. Steps must be taken to prevent further environmental damage and to rehabilitate areas already damaged. Since it is independent of national boundaries, however, attempts to halt the spread of the desert in one area may be negated if nothing is done in an adjacent area. Success is only possible with international cooperation, and economic or political pressure may have to be applied to achieve that. Even if cooperation is complete, however, there is still no guarantee that the problem will be solved. Much will depend upon economic conditions in the developed nations, for they will be required to provide much of the necessary financial aid. Any downturn in the world economy—such as the recession of the early 1990s—puts their contribution in jeopardy, and threatens the success of the fight against desertification.

The great economic gap between rich and poor nations adds to the difficulties of resolving environmental problems at the international level. The developed nations are often accused of asking the Third World to make sacrifices to solve problems that they did little to create. In theory, the benefits would be evenly spread because of the integrated nature of the earth/atmosphere system, but the short-term impact often appears detrimental rather than beneficial. For example, a reduction in the harvesting of tropical hardwoods from the rainforest is the goal of a number of environmental groups in North America and Europe. It would reduce local environmental problems and contribute to the slowing down of global warming. For many tropical nations, however, lumbering in the rainforest is an important source of revenue. They resent outside interference, and point out with justification that their contribution to global warming is minimal compared to that of the industrialized nations. They question the emphasis on the rainforest, when forestry practices in mid to high latitudes also disrupt natural carbon recycling. Similarly, many nations, in which petroleum production and export is the main income earner, resent the imposition of measures—such as carbon taxes—designed to help the environment, but also likely to reduce their revenues and restrict future development.

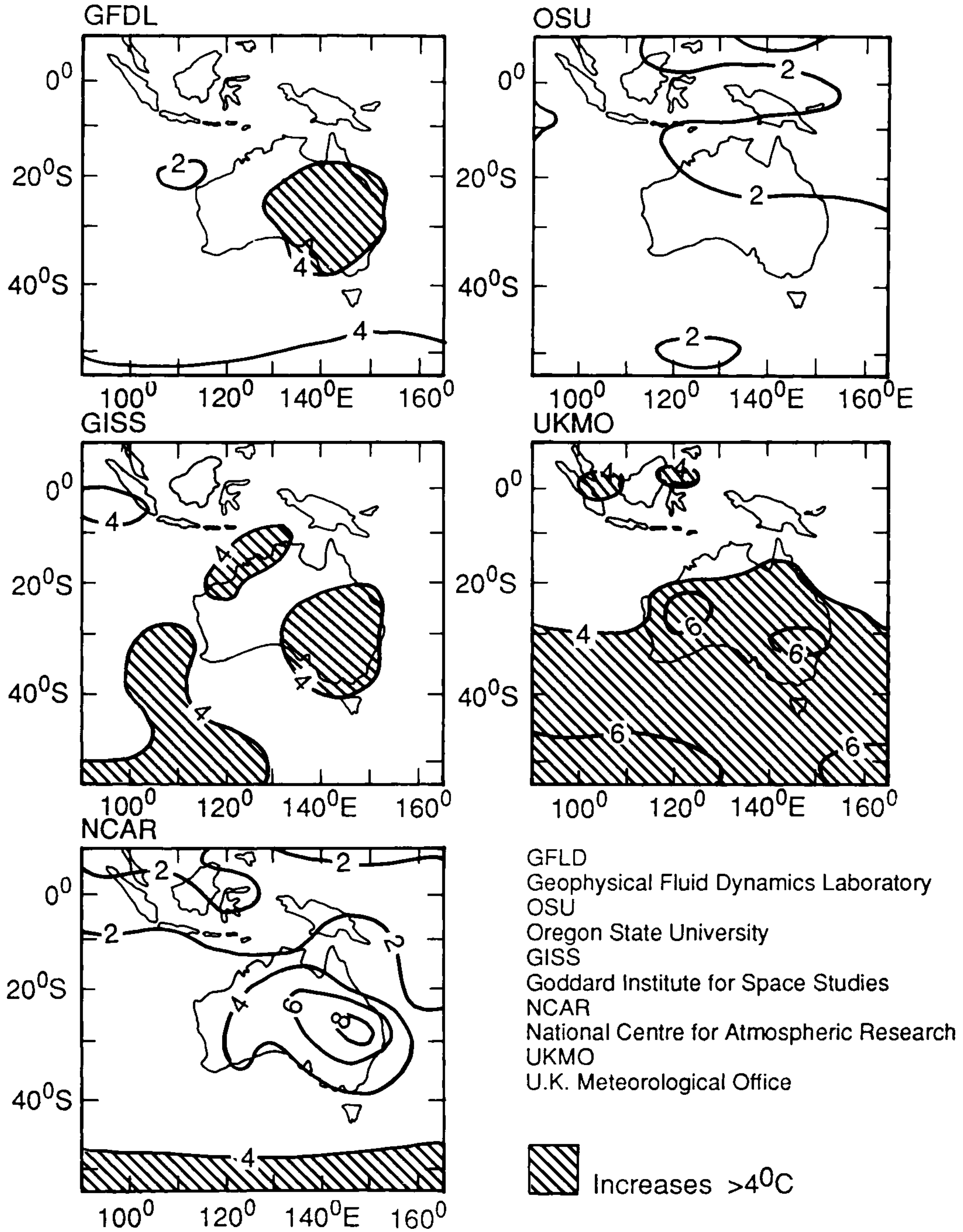
A major concern at the international level is that measures aimed at preserving the environment will impose too high a cost on those least responsible and least able to pay. The challenge will be to define and present the issues in such a way that the nations involved will see it as in their own best interests—economic, social, political and environmental—to introduce measures to prevent further damage to the environment and ameliorate existing problems. This will be no easy task, and although the need for global cooperation to combat global environmental problems is widely recognized, it seems likely that the vagaries of international politics and economics will continue to frustrate attempts to implement solutions.

## FURTHER STUDY: NECESSARY OR NOT?

Current global environmental problems are remarkably complex, and, despite an increasingly intensive research effort, they are even now not completely understood. That situation must change, if solutions are to be found. Almost all individuals and organizations studying the problems have indicated that further study is necessary. In the past, that was often seen as a delaying tactic in that it was often easier to suggest further study than to make a positive attack on a problem. Attempts to solve the acid rain problem in North America were thwarted by these very tactics for many years.

Such arguments are no longer possible now that sufficient data are available, yet there remains a very real need for further study of many aspects of the earth/atmosphere system. The roles of the various atmospheric processes require particular attention since they are intimately involved in all of the major problems currently confronting the environment. Traditionally, the study of the atmosphere was based on the collection and analysis of observational data. That approach is time-consuming and costly; it is also of limited overall accuracy because of gaps in the meteorological network, particularly in high latitudes and over the oceans. Modern attempts at exploring the workings of the atmosphere are almost exclusively dependent upon computer models, which range in complexity from simple 1-D formats providing information on one element in the system to highly sophisticated models employing as many as 100 variables, and including consideration of the oceans as well as the atmosphere. Studies of such topics as nuclear winter, global warming and ozone depletion have benefited greatly from the use of computer modelling techniques. The models are becoming increasingly complex and comprehensive, but a high level of sophistication is no guarantee of perfection. Even state-of-the-art, 3-D general circulation models include some degree of simplification, and certain variables—cloudiness, for example—are very difficult to deal with whatever the level of model employed. In short, there is as yet no model capable of simulating exactly the conditions and processes in the real atmosphere. As a result, models using the same data often generate different results (see Figure 8.2). That should not be used as an excuse to do nothing, however. It might be tempting to wait for the perfect model, but that may prove

*Figure 8.2* GCMs and climate change. Estimates of surface air temperature change over Australia and Indonesia during December, January and February following a doubling of $CO_2$




*Source:* From Henderson-Sellers (1991)

impossible to develop. Existing models do have flaws, but they can be used provided their limitations are understood, and despite their inherent problems there is probably no better way of studying environmental problems involving the atmosphere.

The major tasks facing scientists involved in the study of environmental problems is the reduction of the uncertainty which still clouds some of the issues, despite the ever-increasing complexity and sophistication of current research methods. Scientists can deal with some degree of uncertainty, because they have been trained to accept different levels of confidence in their results. In contrast, planners, politicians and policy-makers must have reliable estimates of the impact of environmental change, if they are to make the decisions necessary to minimize its negative effects and maximize its positive effects. As long as uncertainty exists, it is all too easy to delay action.

This has been a particular problem in the development of strategies for alleviating the effects of global warming. Decision-makers are unwilling to institute measures which will require socio-economic and political sacrifices until they are sure that global warming is a reality. Researchers, unwilling to discard normal scientific caution, cannot give that assurance. In an attempt to find out what would be required to resolve this dilemma, Henderson-Sellers (1990) conducted a survey which included a question about the minimum level of certainty required before action should be initiated to reduce or adapt to global warming. Respondents suggested that a 50 per cent confidence level would be sufficient. Although this is lower than most researchers would accept, it remains difficult to attain. It may take some time for the stand-off between decision-makers and scientists to be resolved, and as an interim measure some researchers have advocated the development of approaches which would alleviate the problem if global warming occurred as projected, yet would have no detrimental effects if it did not. A wide-spectrum solution involving increased energy efficiency is one possibility, for example. Coupled with enhanced multidisciplinary research which acknowledges the complexity of the problem and the wide range of expertise required to respond to it, this approach should at least slow the change until the answer to the uncertainty question can be determined.

Even as better models are developed, and confidence in their results improves, there will be surprises. Current models tend to concentrate on the impact of human interference on the earth/atmosphere system, and generally ignore the possibility that natural variations in the system will instigate change. Most assume that the natural elements in the system will remain benign. Evidence from the earth's past suggests that such an assumption cannot be made. Events such as the eruption of Mount Pinatubo serve as timely reminders that natural events can augment or diminish environmental changes initiated by human activity. It is important, therefore, that even in an increasingly anthropocentric world every attempt be made to identify and understand natural variations in the earth/atmosphere system, both at present and in the past. Only then will it be possible to place human interference in its broader environmental context, and make realistic projections of its future impact.

## SUGGESTIONS FOR FURTHER READING

Buchholz, R., Marcus, A.A. and Post, J.E. (1992) *Managing Environmental Issues: A Casebook,* Englewood Cliffs: Prentice-Hall.

OECD (1991) *Climate Change: Evaluating the Socio-Economic Impacts,* Paris: Organization for Economic Cooperation and Development.

World Resources Institute (1992) *World Resources: 1992–93—A Guide to the Global Environment,* New York: Oxford University Press.

# Glossary

## A

**absorption coefficient** A measure of the degree to which a substance is capable of absorbing radiation.

**acid** A compound containing hydrogen which on solution in water produces an excess of hydrogen *ions*. An acid reacts with a base or *alkali* to form a salt and water.

**acid loading** The addition of acids to waterbodies by way of deposition from the atmosphere.

**acid precipitation** The *wet* or *dry deposition* of acidic substances of anthropogenic origin on the earth's surface. Commonly called *acid rain,* but also includes acid snow and acid fog.

**acid rain** see *acid precipitation* and *wet deposition*.

**actual evapotranspiration** see *evapotranspiration*.

**actuarial drought forecast** An estimation of the probability of drought based upon past occurrences in the meteorological record.

**Advisory Group on Greenhouse Gases (AGGG)** see *Villach Conference*.

**aerosols** Finely divided solid or liquid particles dispersed in the atmosphere.

**Agenda 21** A blueprint for *sustainable development* into the twenty-first century produced at the *United Nations Conference on Environment and Development (UNCED)*.

**albedo** A measure of the reflectivity of the earth's surface. Newly fallen snow reflects most of the *solar radiation* falling on it and has a high albedo; a black asphalt road surface which readily absorbs radiation has a low albedo.

**algae** An order of aquatic plants, occurring in both fresh and salt water.

**alkali** A compound which on solution with water produces an excess of hydroxyl ions (OH).

**Alliance of Small Island States (AOSIS)** A group of states, mainly in the tropics, who consider themselves most likely to suffer the consequences of rising sea level and increased storminess expected to accompany global warming.

**anaerobic decay** The breakdown of organic material in the absence of oxygen. Brought about by anaerobic bacteria, the process commonly causes the production of *methane,* a greenhouse gas.

**Antarctic ozone hole** Intense thinning of the stratospheric *ozone* layer above Antarctica, first reported in the early 1980s by scientists of the British Antarctic Survey at Halley Bay.

**anticyclone** A zone of high atmospheric pressure created by the cooling of air close to the earth's surface (cold anticyclone) or the sinking of air from higher levels in the atmosphere (warm anticyclone). The circulation of air in an anticyclone is clockwise in the northern hemisphere and counter clockwise in the southern hemisphere.

**aquifer** A layer of rock beneath the earth's surface sufficiently porous and permeable to store significant quantities of water.

**Arctic haze** The pollution of the Arctic atmosphere, mainly in winter, by aerosols such as dust, soot and *sulphate particles* originating in Eurasia.

**aridity** Permanent dryness caused by low average rainfall, often in combination with high temperatures.

**atmosphere** The blanket of air which envelops the solid earth. It consists of a mixture of gases and *aerosols*.

**atmospheric circulation** The large scale movement of air around and above the earth, associated with complex but distinct patterns of pressure systems and wind belts.

**atmospheric models** Physical or mathematical representations of the workings of the atmosphere, ranging from regional models such as the midlatitude cyclonic models used in weather forecasting to general circulation models which attempt to represent global circulation patterns.

**atmospheric turbidity** A measure of the dustiness or dirtiness of the atmosphere as indicated by the reduction in solar radiation passing through it.

**atom** The smallest unit of an element that retains the characteristics of that element.

**autovariation** Environmental change produced when one component of the *environment* responds automatically to change in another.

## B

**Biodiversity Convention** A document outlining policies aimed at combining the preservation of natural biological diversity with *sustainable development* of biological resources. A product of *UNCED*.

**biogeophysical feedback mechanism** The hypothesis developed to explain *degradation induced drought* in the *Sahel*. Overgrazing and woodcutting increased the surface *albedo* which in turn disrupted the regional radiation balance. Reduced surface heating retarded convective activity and limited precipitation. With less precipitation, vegetation cover decreased and the *albedo* of the surface was further enhanced. This is an example of positive *feedback*.

**biomass** The total living organic matter in a given area.

**biosphere** The zone of terrestrial life including the earth's surface plus the lowest part of the atmosphere and the upper part of the soil layer.

**bromofluorocarbon** A group of chemicals containing bromine, fluorine and *carbon*. Similar in properties and use to *chlorofluorocarbons*. They decompose to release bromine which contributes to the destruction of the *ozone* layer.

**Brundtland Commission** see *World Commission on Environment and Development*.

**buffering agents** Materials which reduce changes in *pH* when an *acid* or *alkali* is added to a solution or mixture. Alkaline or basic materials are capable of reducing or neutralizing acidity, for example, and natural buffering agents such as limestone help to reduce the environmental impact of *acid rain*.

**'business-as-usua' scenario** A scenario, based on the maintenance of the status quo, used to predict the future status of environmental issues.

## C

**Carbon** A non-metallic element which exists in a variety of forms in the environment. It is chemically mobile, readily combines with other elements and is present in all organic substances.

**carbon cycle** A natural bio-geochemical cycle which works to maintain a balance between the release of carbon compounds from their sources and their absorption in *sinks*.

**carbon cycle models** Computer based models which simulate the workings of the carbon cycle.

**carbon dioxide** One of the variable gases, currently making up 0.0353 per cent of the atmosphere by volume, but growing. Despite its low volume, it is important to life on earth because of its participation in *photosynthesis* and its contribution to the *greenhouse effect*.

**carbon tax** A policy which would tax fossil fuels according to the amount of carbon they contained, the ultimate aim being to reduce *carbon dioxide* emissions and slow the enhancement of the *greenhouse effect*.

**carbon tetrachloride** A solvent and cleaning agent identified as contributing to the depletion of the *ozone* layer.

**carrying capacity** The maximum number of organisms that can be supported by a particular environment.

**cash cropping** Growing crops for monetary return rather than direct food supply. (See also *subsistence farming*.)

**catalyst** A substance which facilitates a chemical reaction, yet remains unchanged when the reaction is over. Being unchanged, it can continue to promote the same reaction again and again, as long as the reagents are available, or until the catalyst itself is removed. This is a catalytic chain reaction.

**Central Electricity Generating Board (CEGB)** The English public utility identified in the 1970s and 1980s as the main source of acid rain falling in Scandinavia.

**chemical models** Models which simulate chemical processes. In studies of the atmospheric environment they are being developed to investigate the role of trace gases in the circulation of the atmosphere.

**chlorine monoxide** A compound containing chlorine and oxygen, which has been implicated in the destruction of *stratospheric ozone*.

**chlorofluorocarbons (CFCs)** A group of chemicals containing chlorine, fluorine and carbon, used in refrigeration and air conditioning systems and in the production of polymer foams. Inert at surface temperature and pressure, they become unstable in the *stratosphere,* breaking down to release chlorine which initiates a catalytic chemical reaction leading to the destruction of *ozone*.

**chloroform** A volatile liquid solvent which contributes to *ozone depletion* through the release of chlorine.

**chlorophyll** A green pigment in plants which makes *photosynthesis* possible through its ability to absorb solar energy.

**circumpolar vortex** A band of strong winds circling the poles in the upper atmosphere. The vortex is mainly a winter phenomenon and best developed around the South Pole.

**Clear Air Legislation** Various laws, acts and ordinances designed to bring about the reduction of atmospheric pollution.

**climate** The combination or aggregate of weather conditions experienced in a particular area. It includes both averages and extremes as measured over an extended period of time.

**Climate Impact Assessment Program (CIAP)** A programme commissioned by the US Department of Transportation in the mid-1970s to study the effects of *supersonic transports (SSTs)* on the *ozone* layer.

**Climatic Optimum** Period of major warming during the immediate post-glacial period between 5,000 and 7,000 years ago.

**coal gasification** The heating or cooking of coal—sometimes in place—to release volatile gases such as *methane,* a cleaner, more efficient fuel than the coal itself.

**coal liquefaction** The conversion of coal into a liquid, petroleum-type fuel by a combination of heating and the use of solvents and *catalysts*.

**Concorde** The most successful of the two types of *supersonic transport* built in the 1970s

**condensation nuclei** Small particles in the atmosphere, of natural or anthropogenic origin, around which water vapour condenses to form liquid droplets.

**continental tropical air mass (cT)** An air mass originating over tropical to sub-tropical continental areas, and therefore hot and dry.

**contingent drought** A type of drought characterized by irregular and variable precipitation in areas which normally have an adequate supply of moisture to meet crop needs.

**convective circulation** Circulation initiated by surface heating which causes the vertical movement of heated air. After cooling the air ultimately returns to the surface to complete the circulation.

**cosmic rays** High-energy radiation reaching the earth from outer space.

**coupled models** Models which combine two or more simulations of elements in the earth/atmosphere system. *Carbon cycle models,* for example, have been combined with oceanic and atmospheric circulation models in the search for a better understanding of global warming.

**coupled ocean/atmosphere climate models** The most common combination in coupled models. The main problem with these models is the difference in time scales over which atmospheric and oceanic phenomena develop and respond to change. Because of the relatively slow response time of the oceanic circulation, the oceanic element in most coupled models is much less comprehensive than the atmospheric element.

**crumb structure** The combination of individual soil particles into loose aggregates or crumbs.

**cyclone** An atmospheric low pressure system, generally circular in shape, with the air-flow counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere and converging towards the centre of the system. Commonly used to refer to intense tropical storms in the Indian Ocean which are the equivalent of Atlantic hurricanes or Pacific typhoons.

## D

**deforestation** The clearing of forested areas as part of a commercial forestry enterprise or for some other economic purpose such as the expansion of settlement or the development of agriculture.

**degradation induced drought** Drought promoted by environmental degradation usually initiated by human activity which disrupts the regional energy and water balances.

**demography** (The study of) statistics on human populations, including such elements as growth rate, age and sex, and their effects on socio-economic and environmental conditions.

**Depression** (The) A period of major economic decline in the 1930s associated with reduced industrial activity, high unemployment and the collapse of international trade.

**desert** An area of permanent *aridity,* characterized by sparse, *xerophytic vegetation,* or, in some areas, by the complete absence of plant life. Almost 30 per cent of the earth's surface exhibits desert characteristics of some form. The world's largest desert is the Sahara, occupying some 8.5 million sq km in North Africa.

**desertification** The expansion of *desert* or desert-like conditions into adjacent areas. May be initiated by natural environmental change, by human degradation of marginal environments or a combination of both.

**Desertification Convention** A proposal presented at *UNCED* aimed at addressing the problems of those areas suffering from desertification.

**diatoms** Microscopic, unicellular aquatic organisms.

**dimethyl sulphide (DMS)** A sulphur compound emitted by phytoplankton during their seasonal bloom. It is oxidized into *sulphur dioxide* and *methane sulphonic acid (MSA).*

**drought** (A period of) reduced water availability occurring when precipitation falls below normal, or when near normal rainfall is made less effective by other weather conditions such as high temperature, low humidity and strong winds.

**drought prediction** The attempt to forecast the occurrence of drought so that responses can be planned and consequences much reduced.

**dry deposition** A form of *acid precipitation* consisting of dry acidic particles. The particles are converted into acids when dissolved in surface water at which time their environmental impact is similar to that of *wet deposition.*

**dry farming** A technique which involves the preservation of several years of *precipitation* to be used for the production of one crop. It includes the use of deep ploughing, to provide a reservoir for the rain that falls, plus a combination of techniques to reduce losses by *evapotranspiration.*

**dry sedimentation** The fallout of dry particulate matter from the atmosphere under the effects of gravity.

**Dustbowl** (The) An area of the *Great Plains,* stretching from Texas in the south to the Canadian Prairies in the north, which suffered the effects of *desertification* in the 1930s. A combination of *drought* and inappropriate farming practices caused the destruction of the *topsoil* and allowed it to be carried away by the wind.

**Dust Veil Index (DVI)** A rating system developed by climatologist H.H.Lamb to provide an assessment of the impact of volcanic eruptions on *atmospheric turbidity* and hence on global *weather* and *climate.*

**dynamic equilibrium** see *environmental equilibrium.*

## E

**earth/atmosphere system** see *system.*

**Earth Summit** Popular name for the *United Nations Conference on Environment and Development (UNCED).*

**easterly tropical** jet A rapidly moving easterly airstream encountered in the upper atmosphere in

**equatorial** latitudes. It is less persistent than *jet streams* in higher latitudes.

**ecosystem** A community of plants and animals interacting with each other and their *environment.*

**El Niño** A flow of abnormally warm water across the eastern Pacific Ocean towards the coast of Peru. It is associated with changing pressure patterns and a reversal of airflow in the equatorial Pacific, a phenomenon referred to as the *Southern Oscillation.*

**electromagnetic spectrum** The arrangement of electromagnetic radiation as a continuum according to wavelength. It extends from high-energy *shortwave radiation* such as *cosmic rays* to the much longer low-energy radio and electric power waves.

**energy budget** The relationship between the amount of solar energy entering the earth/atmosphere system and the amount of terrestrial energy leaving. In theory, these energy fluxes should balance; in practice it applies only in general terms to the earth as a whole, over an extended time period. It is not applicable to any specific area over a short period of time.

**ENSO** An acronym for *El Niño—Southern Oscillation.*

**environment** A combination of the various physical and biological elements that affect the life of an organism. Environments vary in scale from microscopic to global and may be subdivided according to their attributes. The aquatic environment for example, is that of rivers, lakes and oceans, the terrestrial environment that of the land surface. The term 'built' environment has been applied to areas such as cities created by human activity.

**environmental equilibrium** The tendency of the components of the environment to achieve some degree of balance in their relationships with each other. The balance is never complete, but takes the form of a *dynamic equilibrium* which involves a continuing series of mutual adjustments to the relationships.

**environmental impact** studies Analyses of the potential impact of various forms of human activities on the environment.

**environmental lapse rate** The rate at which temperature falls with increasing altitude in the *troposphere*. Although the lapse rate varies with time and place it is normally considered to average—6.5°C per 1,000 m.

**Environmental Protection Agency (EPA)** US agency established in 1970 to coordinate government action on environmental issues.

**equilibrium models** A form of *general circulation model* (GCM). Change is introduced into such a model representing existing climate conditions, and the model is allowed to run until a new equilibrium is established. The new model climate can then be compared with the original to establish the overall impact of the change.

**European Arctic Stratospheric Ozone Experiment (EASOE)** An experiment undertaken during the northern winter of 1991–92, using ground measurements, balloons, aircraft and a variety of modelling techniques to establish the nature and extent of *ozone depletion* over the Arctic.

**evaporation** The process of vaporization by which water changes from a liquid to a gaseous state.

**evapotranspiration** The transfer of water from the terrestrial environment into the atmosphere. It combines *evaporation* from the land surface with *transpiration* from plants. A distinction may be made between actual evatranspiration—a specific measurement—and potential evapotranspiration—an estimate of the environment's capacity for evapotranspiration.

## F

**fallout** The deposition of particulate matter from the atmosphere on to the earth's surface.

**fallow** Arable land left unfilled or tilled, but unsown, for a season. Used in *dry farming* to provide a soil reservoir for precipitation, or in normal arable agriculture to allow the land to recover from the effects of cropping.

**famine** Acute food shortage leading to wide-spread starvation. Usually associated with large scale natural disasters such as *drought*, flooding or plant disease producing crop failure and disruption of food supply.

**feedback** Occurs in integrated systems where change in one part of a system will initiate change elsewhere in the system. This involves the process of *autovariation*. The change may be fed back into the system in such a way as to augment (positive feedback) or diminish (negative feedback) the effects of the original change.

**field capacity** see *soil moisture storage*.

**flue gas desulphurization (FGD)** The process by which sulphur dioxide is removed from exhaust gases produced by the burning of coal. (See also *scrubbers*.)

**fluidized bed combustion (FBC)** The burning of a mixture of crushed coal, limestone and sand in the presence of high pressure air which causes the mixture to behave like a boiling liquid. Continual mixing ensures that combustion is very efficient, with up to 90 per cent of the sulphur in the fuel being absorbed by the limestone.

**fossil fuels** Fuels formed from organic material, which was buried by sediments and retained its stored energy. It is that energy which is released when fossil fuels are burned. Fossil fuels include coal, oil and gas, the main energy sources in advanced industrial societies. Fossil fuel consumption is a major contributor to a number of current environmental issues including *acid rain, atmospheric turbidity* and *global warming*.

**Framework Convention on Climate Change** One of the conventions signed at the *Earth Summit*. It grew out of concern for *global warming*, but was signed only after much controversy and ended up as a relatively weak document lacking even specific emission reduction targets and deadlines.

**Freon** The commercial name for *chlorofluorocarbons (CFCs)*.

**fuel desulphurization** The reduction in the sulphur content of fuels such as coal and oil prior to combustion, (see also *coal gasification* and *coal liquefaction*.)

**fuel switching** One of the simplest approaches to the control of acid gas emissions. It involves the replacement of high sulphur fuels with low sulphur alternatives.

**fuelwood** Wood products harvested for use as fuel. The removal of scrub woodland for fuelwood is a major cause of *desertification* in the arid or semiarid parts of Africa and Asia.

## G

**Gaia hypothesis** Developed by James Lovelock, the hypothesis views the earth as a superorganism in which the living matter is capable of manipulating the earth's environment to meet its own needs.

**gas phase reaction** The conversion of *sulphur dioxide* and *oxides of nitrogen* into sulphuric and nitric acid, all of the reactions taking place with the various compounds remaining in a gaseous state.

**general circulation models (GCMs)** Three-dimensional models which incorporate major atmospheric processes plus local climate features predicted through the process of *parameterization*. They include some representation of *feedback* mechanisms and are able to cope with the evolving dynamics of the atmosphere as change takes place. In an attempt to emulate the integrated nature of the earth/atmosphere system atmospheric GCMs are often coupled with other environmental models, particularly those representing the oceans.

**Glaciological Volcanic Index (GVI)** An index based on acidity levels in glacial ice as revealed by ice cores. This gives an indication of *sulphur dioxide* levels associated with past volcanic eruptions, an element absent from both the *Dust Veil Index* and the *Volcanic Explosivity Index*.

**Global Forum** A conference of non-government organizations (NGOs) held at the same time as the *United Nations Conference on Environment and Development (UNCED)*. It included a wide range of topics—from the presentation of biological diversity to *sustainable development*—which generally paralleled those included in the main UNCED event.

**global warming** The rise in global mean temperatures of about 0.5°C since the beginning of the century. The basic cause of the warming is seen by many researchers as the enhancement of the *greenhouse effect* over the same period, brought on by rising levels of anthropogenically-produced *greenhouse gases*.

**Great American Desert** Common perception of the western interior plains of North America in the nineteenth century. The image grew out of the reports of exploratory expeditions which visited the plains during one of the periods of *drought* common to the area, and observed the results of natural *desertification*.

**Great Plains** An area of temperate grassland with a semi-arid climate in the interior of North America, stretching for some 2,500 km from western Texas in the south along the flanks of the Rocky Mountains to the Canadian prairie provinces in the north. (See also *Great American Desert, Dustbowl* and *Pueblo drought*.)

**Green Parties** Political organizations which aim to protect the environment through the use of established parliamentary procedures.

**greenhouse effect** The name given to the ability of the *atmosphere* to be selective in its response to different types of radiation. Incoming short-wave *solar radiation* is transmitted unaltered to heat the earth's surface. The returning long-wave *terrestrial radiation* is unable to penetrate the *atmosphere,* however. It is absorbed by the so-called *greenhouse gases* causing the temperature of the *atmosphere* to rise. Some of the energy absorbed is returned to the earth's surface, and the net effect is to maintain the average temperature of the earth/ atmosphere system some 30°C higher than it would be without the greenhouse effect. The process has been likened to the way in which a greenhouse works—allowing sunlight in, but trapping the resulting heat inside—hence the name.

**greenhouse gases** The group of about twenty gases responsible for the *greenhouse effect* through their ability to absorb long-wave *terrestrial radiation*. They are all minor gases and together make up less than 1 per cent of the total volume of the atmosphere. *Carbon dioxide* is the most abundant, but *methane, nitrous oxide,* the *chlorofluorocarbons* and tropospheric *ozone* also make significant contributions to the *greenhouse effect*. Water vapour also exhibits greenhouse properties, but has received less attention than the others. Since the beginning of the twentieth century, rising levels of these gases in the atmosphere, associated with increasing *fossil fuel* use, industrial development, *deforestation* and agricultural activity, have brought about an enhancement of the *greenhouse effect,* and have contributed to gradual *global warming*.

**grid-point models** Climate models which provide full spatial analysis of the atmosphere by means of a three-dimensional grid covering the earth's surface and reaching as high as 30 km into the atmosphere. The progressive solution of thousands of equations at each of these points allows powerful computers to provide simulations of current and future climates.

**ground control** The use of observation and measurement at the earth's surface to verify information provided by *remote sensing* from satellites or aircraft.

**groundwater** The water which accumulates in the pore spaces and cracks in rocks beneath the earth's surface. It originates as *precipitation* which percolates down into sub-surface *aquifers*. The upper limit of groundwater saturation is the water-table.

**growing season** The period of the year when mean daily temperatures exceed the temperature at which plant growth takes place. Since different plants mature at different rates, the length of the growing season will determine the mix of natural vegetation and the types of crop that will grow in a particular area.

**Gulf Stream** A warm ocean current, originating in the eastern Caribbean, which flows north along the eastern seaboard of the United States before swinging north-eastwards into the Atlantic Ocean where it becomes the weaker and cooler North Atlantic Drift.

## H

**Hadley cells** Convection cells which form in the tropical atmosphere north and south of the equator. Named after George Hadley who, in the eighteenth century, developed the classic model of the general circulation of the atmosphere based on a simple *convective circulation*.

**halons** Synthetic organic compounds containing bromine. Commonly used in fire extinguishers, they are more effective in destroying the *ozone* layer than *chlorofluorocarbons*. (See also *bromofluorocarbons*.)

**Harmattan** A hot, dry, dusty wind which blows out of the Sahara Desert over the *Sahel* and much of West Africa during the northern hemisphere winter. It brings *continental tropical air* southwards which contributes to the *seasonal drought* characteristic of the area.

**heavy metals** Metals such as mercury, lead, tin and cadmium which may be converted into a soluble organic form or concentrated by hydrological or biological processes so that they become hazardous to natural ecosystems and human health.

**heterogeneous chemical reactions** Chemical reactions which take place on the surface of the ice particles that make up *polar stratospheric clouds,* leading to the release of chlorine which attacks the *ozone* layer. Similar reactions have been identified on the surface of stratosphere sulphate particles such as those released during the eruption of Mount Pinatubo in 1991.

**humidity** A measure of the amount of water vapour in the atmosphere. It may be expressed as specific humidity—the ratio of the weight of water vapour in the air to the combined weight of the water vapour and the air—or as relative humidity—the amount of water vapour in the air compared to the amount of water vapour the air can hold at that temperature.

**humus** Partially decomposed organic matter which is an essential component of fertile soil.

**hydrocarbons** Organic compounds composed of hydrogen and carbon bound together in chains or rings. The largest sources of hydrocarbons are *fossil fuels* such as petroleum and natural gas.

**hydrochlorofluorocarbons (HCFCs)** A widely-used substitute for *chlorofluorocarbons (CFCs)*. Being less stable than CFCs, hydrochlorofluorocarbons begin to break down in the troposphere before they can diffuse into the stratosphere and destroy the *ozone* layer. They are about 95 per cent less destructive than CFCs.

**hydrogen oxides** A group of naturally occurring compounds, derived from water vapour, methane and molecular hydrogen, which can destroy *ozone* through catalytic chain reactions (see *catalyst*). They include atomic hydrogen, the hydroxyl radical and the perhydroxyl radical, referred to collectively as odd hydrogens.

**hydrologic cycle** A complex group of processes by which water in its various forms is circulated through the earth/atmosphere system. It is powered by *solar radiation* which provides the energy to maintain the flow by way of such processes as *evaporation, transpiration, precipitation* and *runoff*. Short- and long-term storage of water in lakes, oceans, ice sheets and the *groundwater reservoir* is also part of the cycle.

**hydroxyl radical** (See *hydrogen oxides*.)

## I

**Ice Ages** Periods in the geological history of the earth when glaciers and ice sheets covered large areas of the earth's surface. The Ice Ages occurred in series, separated by periods of temperate conditions called interglacials. The most recent series began some

3.5 million years ago and persisted until 10,000 years ago causing major disruption of land-forms, drainage, animal communities and vegetation.

**index cycle** See *zonal index*.

**Industrial Revolution** A period of rapid transition from an agricultural to an industrial society, beginning in Britain in the mid-eighteenth century, and spreading to other parts of the world in the next two hundred years. It was characterized by a major expansion in the use of coal as a fuel, in the steam engine and in the iron industry. Although the Industrial Revolution was a period of great technical achievement and economic development, it also marked the beginning of increasingly serious environmental deterioration. Current environmental issues such as *acid rain, global warming* and *atmospheric turbidity* have their roots in activities initiated or expanded during the Industrial Revolution.

**infrared radiation** Low-energy, long-wave radiation with wavelengths between 0.7 and 1,000 μm. *Terrestrial radiation* is infrared. It is captured by the atmospheric *greenhouse gases* and as a result is responsible for the heating of the earth/atmosphere system.

**insolation** *Solar radiation* entering the atmosphere.

**interactive models** *General circulation models* which are programmed to deal with the progressive change set in motion when one or more of the components of the *atmosphere* is altered.

**Intergovernmental Panel on Climate Change (IPCC)** A group of eminent scientists brought together in 1988 by the *World Meteorological Organization (WMO)* and the *United Nations Environment Program (UNEP)*. It was charged with assessing the overall state of research on climate change so that potential environmental and socio-economic impacts might be evaluated, and appropriate response strategies developed. Three reports were produced in 1990 and 1991.

**Intertropical Convergence Zone (ITCZ)** A thermal low-pressure belt which circles the earth in equatorial latitudes. It owes its origin to convective uplift caused by strong surface heating, augmented by converging air-flows from the northeast and southeast Trade Winds. It lies between the tropical *Hadley Cells* positioned north and south of the equator. The ITCZ moves north and south with the seasons bringing the rains to areas of *seasonal drought* to areas such as the *Sahel,* India and northern Australia.

**invisible drought** A form of *drought* that can be identified only by sophisicated instrumentation and statistical techniques. There may be no obvious lack of *precipitation,* but moisture requirements are not being met, the crops are not growing at their optimum rate, and the potential yield is therefore reduced.

**ion** An *atom* or group of atoms that has become electrically charged by picking up or losing electrons. Ions formed from metals are generally positively charged (cations); those from non-metals are negatively charged (anions).

**IPCC Supplementary Report** A report issued in 1992 by the *Intergovernmental Panel on Climate Change* which generally confirmed the results of its earlier assessments.

**irrigation** The provision of water for crops in areas where the natural *precipitation* is inadequate for crop growth.

**isothermal layer** An atmospheric layer in which the lapse rate is neutral, that is the temperature remains constant with increasing altitude. (See also *environmental lapse rate*.)

## J

**jet stream** A fast flowing stream of air in the upper atmosphere at about the level of the *tropopause*. Two well-defined jet streams, flowing from west to east in a sinuous path around the earth, are located in sub-tropical latitudes (the sub-tropical jet) and in mid to high latitudes (the polar front jet). An *easterly tropical jet* has also been identified.

## K

**Krakatoa** A volcanic island in the Sunda Strait, Indonesia which erupted explosively in 1883 sending several tonnes of debris high into the atmosphere. The volcanic dust circled the earth, remaining in the upper atmosphere for several years where it increased *atmospheric turbidity*.

## L

**La Niña** An intermittent cold current flowing from east to west across the equatorial Pacific Ocean, in those years when *El Niño* is absent. It is caused by strong equatorial easterly winds pushing cold water upwelling off the South American coast, far out into the ocean. Its influence appears to extend beyond the Pacific, being associated with increased precipitation in the *Sahel* and India.

**latent heat** The quantity of heat absorbed or released by a substance during a change of state. Latent heat of fusion is involved in the transformation of a solid into a liquid (or liquid into a solid) as in the ice-water-ice transformation. Latent heat of vaporization is the equivalent in changes involving liquids and gases, such as water and water vapour.

**leaching** The removal of soluble minerals from soil by percolating water. Leaching is commonly accelerated in soils subject to acid precipitation.

**leguminous plants** A group of pod (or legume) bearing plants of the pea family. Nodules on the roots of leguminous plants contain nitrogen-fixing bacteria which have an important role in the earth/atmosphere nitrogen cycle.

**lime injection multi-stage burning (LIMB)** A technique developed to reduce acid gas emissions from coal burning furnaces. Fine lime is injected into the combustion chamber where it fixes the sulphur released from the burning coal, thus reducing *sulphur dioxide* emissions by 35–50 per cent.

**limestone** A sedimentary rock consisting mainly of calcium carbonate. When limestone is heated, carbon dioxide is driven off and calcium oxide or lime is left. Lime has been used for centuries to sweeten acid soils, and as an *alkali* it is widely used to neutralize the acid gas emissions responsible for *acid rain*.

**liquid phase reaction** The conversion of acid gases into liquid acids, the reactions taking place in solution. (See also *gas phase reaction*.)

**Little Ice Age** A period of global cooling lasting for about 400 years from the mid-fourteenth to the mid-eighteenth century.

**Live Aid** An organization set up in 1985 to help the victims of drought and famine in Ethiopia. It raised money through two major concerts in England and the United States at which the leading popular entertainers of the day performed.

**London Smog (1952)** A major pollution event in London, England caused by a combination of meteorological conditions (low temperatures, high pressure, poor ventilation) and energy use (the burning of high-sulphur coal). An estimated 4,000 deaths were attributed to the smog.

**Long Range Transportation of Air Pollution (LRTAP)** The transportation of air pollution over great distances—usually in excess of 500 km—by the prevailing winds in the atmosphere. Aggravated by the introduction of the *tall stacks policy,* which increased the height of emissions, encouraged LRTAP and contributed to the spread of *acid rain* damage.

**long-wave radiation** Relatively low energy radiation from the *infrared* sector of the electromagnetic spectrum. *Terrestrial radiation* is long-wave.

## M

**malnutrition** A result of the consumption of essential nutrients at levels inadequate to maintain good health.

**maritime tropical air mass (mT)** An air mass originating over the oceans in tropical latitudes, and therefore hot and moist. mT air is also inherently unstable and capable of producing large amounts of precipitation.

**melanoma** A malignant, normally fatal form of skin cancer, associated with over-exposure to ultraviolet-B radiation. (See also *skin cancer*.)

**mesopause** The boundary between the *mesosphere* and *thermosphere* lying some 80 km above the earth's surface.

**mesosphere** The layer of the atmosphere lying above the *stratosphere*. In it temperatures decline with increasing altitude from close to 0°C at the *stratopause* to-80°C at the *mesopause*.

**methane** A simple hydrocarbon gas produced during the decomposition of organic material under anaerobic conditions. It is a powerful *greenhouse gas,* being about twenty-one times more effective than *carbon dioxide,* molecule for molecule, and increasing more rapidly.

**methane sulphonic acid (MSA)** a gas produced by the oxidization of *dimethyl sulphide (DMS)* released by *phytoplankton* during their seasonal bloom. MSA is ultimately converted into sulphate in the atmosphere, therefore adding to natural atmospheric acidity.

**methyl bromide** A fumigant which may be responsible for as much as 10 per cent of existing ozone depletion. It is used to kill pests in the fruit and vegetable industry.

**mid-latitude frontal model** A model of mid-latitude cyclonic circulation developed between 1915 and 1920 by Norwegian weather forecasters. It identified the interactions between the air masses in a mid-latitude cyclone and explained the resulting weather patterns. It remained an important forecasting tool in mid-latitudes for at least 50 years and the elements of the model—such as cold front, warm front, warm sector—remain very much part of the current weather forecasting vocabulary.

**models** Idealized, and usually simplified, representations of complex phenomena, models are used to describe and explain as well as forecast the effects of change. Models have been used extensively in attempts to unravel the complexity of the earth/ atmosphere system. (See also e.g. *carbon cycle models, climate models, coupled models, coupled ocean/atmosphere, general circulation models*.)

**moisture deficit** In theory a moisture deficit exists in a region when *evapotranspiration* exceeds *precipitation*. However, all soils have the ability to store moisture which will offset the effects of any deficit. As a result, a true deficit may not exist until the soil water storage has been used up, and for most practical purposes—drought evaluation, for example—the focus is on *soil moisture deficit (SMD)* rather than the simple relationship between *precipitation* and *evapotranspiration*.

**moisture index** A representation of moisture availability in an area, often used in *drought* and *aridity* studies. Most indices incorporate a combination of meteorological elements including *precipitation, evapotranspiration, solar radiation,* temperature and wind speed.

**moisture surplus** A moisture surplus exists in a region when *precipitation* exceeds *evapotranspiration,* and when the *soil moisture storage* is full. Any additional precipitation will flow across the surface as *run-off into* rivers and lakes.

**molecule** The smallest part of a compound which retains the composition and chemical properties of the compound.

**Montreal Protocol** An agreement reached in Montreal, Canada in 1987 aimed at reducing the destruction of the *ozone* layer. The signatories agreed to a 50 per cent cut in the production of *chlorofluorocarbons* by the end of the century.

## N

**natural environment** see *environment*

**necrosis (of leaf tissue)** The disintegration of leaf tissue caused by the degeneration of cells in direct contact with *acid precipitation*.

**nitric oxide (NO)** One of the *oxides of nitrogen,* in which each *molecule* consists of one *atom* of nitrogen and one of *oxygen*. An important natural, ozone destroying gas responsible for perhaps as much as 50–70 per cent of the natural destruction of *stratospheric ozone,* through a long catalytic chain reaction.

**nitrifying bacteria** A group of bacteria found in soil and in the root nodules of *leguminous plants,* which are capable of fixing the atmospheric *nitrogen* essential for the creation of the complex nitrogen-based compounds found in all forms of life.

**nitrogen** A colourless, odourless gas which makes up about 78 per cent of the volume of the *atmosphere*. Molecular nitrogen is inert and may be considered as a dilutant for the oxygen with which it shares most of the atmosphere. When it does combine with oxygen it forms *oxides of nitrogen,* a group of gases involved in a number of current environmental problems.

**nitrogen dioxide ($NO_2$)** A red-brown toxic gas, in which each *molecule* consists of one *atom* of *nitrogen* and two of *oxygen*. It is a major constituent of automobile exhaust gases and a common component of urban *photochemical smog*.

**nitrogen oxides see** *oxides of nitrogen*.

**nitrous oxide ($N_2O$)** One of the *oxides of nitrogen* in which each *molecule* consists of two *atoms* of *nitrogen* and one of *oxygen*. Nitrous oxide is a naturally produced *greenhouse gas,* but owes its current growth to the increased use of agricultural fertilizers and the burning of *fossil fuels*.

**nomadism** A way of life in which groups of people move from place to place in search of food for themselves or their animals. Before the development of agriculture, nomadic hunting groups were the norm.

**normals (climate)** Data representing average climatic conditions. Usually calculated over a thirty-year period.

**North American Water and Power Alliance (NAWAPA)** A scheme to divert Canadian rivers, flowing into the Arctic Ocean, southwards into the United States, by means of a continental-scale network of reservoirs, canals, aqueducts and pumping stations. The main purpose of the scheme was the provision of water for irrigation and municipal supply in the arid west and southwest of the United States. It was not developed beyond the planning stage.

**nuclear autumn (fall)** see *nuclear winter*.

**nuclear winter** The result of rapid cooling brought on by increased *atmospheric turbidity* and reduced *insolation* following a major nuclear war. Model simulations predicted such a rapid decline in *insolation* that temperatures would fall to winter levels even in mid-summer. One subsequent modification suggested that cooling would be less than first expected, with temperatures declining to values more common in autumn or fall than in winter—hence the term *nuclear autumn (fall)*. (See also *TTAPS scenario*.)

## O

**oceanic circulation** The movement of water in the earth's ocean basins. The surface circulation is caused mainly by wind setting the surface water layers in motion in the form of distinct currents, whereas the deeper ocean circulation is associated mainly with differences in water density caused by changing temperature and salinity.

**odd hydrogens** see *hydrogen oxides*.

**open system** A system in which there is free transfer of energy and matter across the system boundaries.

**overpopulation** A situation in which the population exceeds the *carrying capacity* of the environment.

**oxidation** The combination of *oxygen* with another element to form an oxide.

**oxides of nitrogen** A group of gases formed by the combination of *oxygen* and *nitrogen*. They include *nitric oxide, nitrous oxide* and *nitrogen dioxide*.

**oxygen** A colourless, odourless gas which makes up 21 per cent of the volume of the atmosphere. The amount of oxygen in the air is kept relatively constant through the process of *photosynthesis*. It is a highly reactive chemical combining readily with other elements to form oxides. Oxygen is essential for life on earth, being absorbed by animals during respiration and used to release energy in reactions with other chemicals.

**ozone** A form of oxygen in which each *molecule* contains three *atoms* rather than the two of normal atmospheric *oxygen*. It is a blue gas with a pungent odour and a very powerful oxidizing agent. In the *troposphere* it is normally considered a pollutant, but a layer of ozone in the *stratosphere* protects the earth's surface by absorbing *ultraviolet radiation*.

**ozone depletion** The damage to the stratospheric *ozone* layer caused by the growing volume of ozone-destroying chemicals in the atmosphere.

**Ozone Protection** Act Legislation passed by the Australian government in 1989 aimed at eliminating *chlorofluorocarbon* and *halon* use by 1994, to protect the ozone layer from further depletion.

## P

**parameterization** The method by which regional scale processes are included in global climate models. For example, cloudiness, which is very much a local factor can be represented using temperature and humidity values calculated at the model grid points.

**particle coagulation** An atmospheric cleansing process in which individual particles floating in the atmosphere combine together to form larger particles which are too heavy to remain suspended, and under the effect of gravity fall back to the surface.

**particulate matter** A collective name for all forms of material added to the atmosphere by processes at the earth's surface.

**pastoral agriculture** A form of agriculture, based on the herding of grazing animals such as cattle, sheep, goats and camels, common in semi-arid tropical and temperate natural grasslands.

**permanent drought** A form of drought under which agriculture is not normally possible, since there is insufficient moisture for anything but the *xerophytic vegetation* which has adapted to the arid environment.

**pH** (**potential hydrogen**) The representation of the acidity or akalinity of a substance on a logarithmic scale of 0 to 14 based on hydrogen *ion* concentration. Acid substances have pH values between 0 and 7; alkaline substances range between 7 and 14 and a pH of 7 is considered neutral.

**photochemical processes** Chemical processes induced by the presence of sunlight, which provides the energy required for the reactions involved.

**photochemical smog** *Smog* produced by the action of *photochemical processes* on primary combustion products, particularly the *hydrocarbons* and *oxides of nitrogen,* produced by the internal combustion engine.

**photosynthesis** A biochemical process in which green plants absorb solar radiation and convert it into chemical energy. It is made possible by *chlorophyll.* During the process *carbon dioxide* and water are consumed, carbohydrates are produced and stored, and *oxygen* is released, helping to maintain the *oxygen/carbon dioxide* balance in the atmosphere.

**phytoplankton** Microscopic plants which live in the upper layers of the oceans.

**polar stratospheric clouds** Clouds of ice particles which form in the *stratosphere* above the poles during the winter, (see also *heterogeneous chemical reactions*.)

**pollution (environmental)** The contamination of the physical and biological components of the earth/ atmosphere system to such an extent that normal environmental processes are adversely affected.

**polymer foams** Synthetic foam produced by bubbling *chlorofluorocarbons* through liquid plastic.

**potential evapotranspiration (PE)** The amount of *evaporation* and *transpiration* that will take place if sufficient moisture is available to fill the environment's capacity for *evapotranspiration*. Measurable *evaporation* ceases when water is no longer available, but the environment may retain the ability to cause additional *evapotranspiration* through such elements as temperature, radiation, humidity and wind. Potential evapotranspiration is the theoretical value that represents that ability.

**pre-Cambrian Shield** An area of ancient, acidic rocks, mainly igneous and metamorphic in origin, formed perhaps as early as 4.5 billion years ago. Long exposure to erosion has worn them down to the subdued rounded landscapes found in northern Canada, Sweden and Finland.

**precipitation** Any solid or liquid water particles falling to the earth's surface from the atmosphere. It includes rain, snow, hail and sleet.

**precipitation scavenging** A process by which rain and snow wash particulate matter out of the atmosphere, thus helping to cleanse it.

**primary aerosols** Large particles with diameters between 1 and 100 μm. They include soil, dust and a variety of industrial emissions formed by the breakup of material at the earth's surface.

**Pueblo drought** A serious drought which struck the territory of the Pueblo group of Indian tribes in the south-western United States in the thirteenth century.

## R

**radiation absorption** The intake of radiant energy by an object, causing the temperature of the object to rise, and allowing it to become a radiating body in its own right.

**radiation blindness** Loss of sight caused by damage to the eye from exposure to excess solar radiation. It usually takes the form of cataracts in which the normally clear lens of the eye becomes opaque, causing reduced light transmission and loss of visual perception.

**radiation scattering** The disruption of the smooth flow of radiation through the atmosphere, usually as a result of *paniculate matter* in the energy path.

**radiation spectrum** see *electromagnetic spectrum*.

**radiative-convective models** One-dimensional climate models incorporating global-scale radiative and convective processes at different levels in the *atmosphere,* used to estimate temperature change initiated by changing atmospheric *aerosol* levels.

**radiative forcing agent** Any factor capable of disturbing the energy balance of the earth/ atmosphere system.

**RAINS** A computer model developed to study *acid rain* in Asia. Similar to a model developed for the European Community, it will allow researchers to alert Asian governments to the extent and intensity of the problem.

**recharge rate** The rate at which water withdrawn from the *groundwater* system is replaced by *precipitation*.

**recycling** The recovery of waste material for reprocessing into new products, or the reuse of discarded products.

**remote sensing** The observation of the surface of the earth from a distance by means of sensors. Aerial photography was the earliest form of remote sensing, but satellite observation is now most common, involving the creation of simple photographic images or the collection of data in digital form.

**retrofitting** The adaptation of an existing structure or appliance to meet needs which did not exist when the structure or appliance was first constructed.

**Rio Declaration** A declaration of global principles on the theme of economically and environmentally sound development. Along with *Agenda 21,* it represented the culmination of the activities of the *United Nations Conference on Environment and Development (UNCED)*.

**Rossby waves** Longwaves in the circumpolar westerly airflow in the upper atmosphere, first described by Carl Rossby in the 1930s. The flow pattern followed by the waves is quite variable and difficult to forecast, but it makes a major contribution to meridional energy transfer in mid to high latitudes (see also *zonal index*.)

**Run-off** See *moisture surplus*.

## S

**Sahel** A semi-arid to arid area, subject to seasonal and long-term drought, in Africa south of the Sahara Desert. The Sahel proper consists of the six nations, Senegal, Mauretania, Mali, Burkina Faso, Niger and Chad, but the name has come to include adjacent nations which suffer from problems of *drought, famine* and *desertification* which are characteristic of the Sahel.

**salinization** The build-up of salts in soils as a result of the evaporation of *irrigation* water.

**scrubbers** Structures used to reduce acid-gas emissions from industrial plants. Wet or dry techniques can be used, but all involve bringing the gases in contact with alkaline or basic substances which neutralize their acidity.

**sea-ice models** Models which attempt to simulate the role of sea-ice in global climates. They may be incorporated in ocean models or coupled directly to *general circulation models*.

**sea-surface temperatures (SSTs)** A source of information on potential change in the earth/atmosphere system. Anomalous warming or cooling of the sea surface, for example, may be followed some time later by changing pressure, wind and precipitation patterns. Once the initial change has been identified such time-lags allow subsequent events to be predicted.

**seasonal drought** Regularly occurring *drought* restricted to one season of the year and offset by a distinct rainy season. Seasonal drought is common in the tropical and sub-tropical grasslands of Africa, India and Australia where dry conditions are brought on by the arrival of *continental tropical air* as the *Intertropical Convergence Zone* advances equatorwards.

**secondary aerosols** Aerosols formed as a result of chemical and physical processes in the atmosphere. They are concentrated in the size range of 0.1–1 μm and may make up as much as 64 per cent of total global aerosols.

**selective catalytic reduction (SCR)** An efficient but costly process developed to reduce the emission of *oxides of nitrogen* from power plants. With the help of a *catalyst*, the *oxides of nitrogen* are broken down into harmless *nitrogen* and *oxygen*.

**sensible heat** Heat which can be felt or sensed, and which causes the temperature of a body to change shifting sands A popular image of desertification in which desert sand dunes migrate into an area, covering arable land and pasture and sometimes settlements, thus creating a *desert*.

**short-wave radiation** Radiation from the high energy end of the *electromagnetic spectrum*. The term is commonly applied to *solar radiation* which consists of *ultraviolet* and *visible light* rays.

**sink** Natural reservoir or store for materials circulating through the earth/atmosphere system. The oceans are a major natural sink for many substances from *heavy metals* to *carbon*.

**skin cancer** A disease indicated by the alteration of skin cells and associated with damage to the genetic make-up of the cells. Levels of skin cancer have been rising since the late 1970s, apparently in parallel with the thinning of the *ozone* layer, which has allowed the *ultraviolet radiation* reaching the earth's surface to increase. (See also *melanoma*.)

**'slab' models** Interactive atmosphere-ocean circulation models in which the ocean is represented by only the uppermost layer or 'slab' of water. This is necessary to accommodate the different response times of atmosphere and ocean.

**smog** A combination of smoke and fog which creates atmospheric pollution.

**soil erosion** The removal of *topsoil* by water, wind and gravity at a rate greater than it can be formed.

**soil moisture deficit (SMD)** A measure of moisture availability used in drought evaluation. It incorporates not only traditional elements such as *evapotranspiration* and *precipitation,* but also considers the nature and state of crop development—which influences moisture requirements—and the storage capacity of the specific soil.

**soil moisture storage** Water held in the pore spaces of the soil. In arid areas it offsets the *water deficit* caused when *evapotranspiration* exceeds *precipitation*, and delays the onset of *drought*. When the soil moisture storage is full the soil is said to be at *field capacity*.

**soil structure** The form of the aggregates produced when individual soil particles clump together. Aggregates may be crumbs, blocks or plates, for example.

**soil texture** A measure of the proportions of sand, silt and clay in a soil.

**solar radiation** Radiant energy given off by the sun. Since the sun is a very hot body, the bulk of the radiation is high energy at *ultraviolet* and *visible light* wavelengths.

**soot** Finely divided particles of carbon formed during combustion, which readily combine with each other into clusters or strings, and are effective at absorbing radiation across the entire spectrum.

**Southern Oscillation** The periodic reversal of pressure patterns and wind directions in the atmosphere above the equatorial Pacific Ocean. Part of the *Walker Circulation* and responsible for the development of *El Niño*. (See also *ENSO*.)

**spatial resolution** An indication of the detail available from weather and climate models, determined by the horizontal and vertical distribution of the grid points for which data are available, and at which the appropriate equations are solved.

**spectral models** Atmospheric circulation models which focus on the representation of atmospheric disturbances or waves by a finite number of mathematical functions. The progressive solution of a series of equations allows the development of the atmospheric disturbances to be predicted.

**sphagnum** A type of moss which is a common component of the plant community in temperate peat bogs. Being acid tolerant it colonizes the margins of acid lakes.

**spring flush** The rapid run-off of water from melting snow and ice, common in mid to high latitudes at the end of winter, which carries the winter's accumulation of acidity into rivers and lakes in a matter of days, rapidly reducing the *pH* of these waterbodies.

**Statement of Forest Principles** A general statement from the *Earth Summit* which acknowledges the need to balance exploitation and conservation of forests, but with no provision for international monitoring or supervision.

**steady state system** A *system* in which inputs and outputs are equal and constant, and in which the various elements are in equilibrium. Any change alters the relationships among the components of the system, creating imbalance, and setting in train a series of reponses which attempt to restore balance.

**steppe** A semi-arid area characterized by short-grass vegetation. Considered transitional between desert and sub-humid climates. In areas closer to the latter, steppe may include woody shrubs.

**stratopause** The boundary between the *stratosphere* and *mesosphere,* located at about 50 km above the earth's surface.

**stratosphere** The layer of the atmosphere lying above the *tropopause*. It is characterized by an isothermal layer (temperatures remain constant) up to about 20 km above the earth's surface, beyond which temperatures rise again from about-50°C to reach close to 0°C at the *stratopause*. This is the result of the presence of ozone which absorbs incoming *ultraviolet radiation,* causing temperatures to rise.

**stratospheric ozone** See *ozone*.

**strip-cropping** The practice of cultivating land in long narrow strips of different crops, to ensure that the land always retains some vegetation cover, and is therefore protected from *soil erosion*.

**Study of Critical Environmental Problems (SCEP)** Produced in 1970, this was the first major study to draw attention to the global extent of human-induced environmental issues.

**Study of Man's Impact on Climate (SMIC)** A 1971 report which grew out of issues raised originally in the *SCEP*. It focused on inadvertent climate modification.

**subsidence** The sinking of air in the atmosphere. Subsidence may be associated with the cooling of air close to the surface—as in cold an*ticyclones*—or with the larger scale circulation—in the descending arm of a convection cell, for example.

**subsistence farming** The production of sufficient food and other necessities to meet the requirements of a farm unit, leaving no surplus for sale and little for storage.

**sulphate (particle)** A negatively charged *ion* containing one *atom* of sulphur and four of *oxygen*.

**sulphur** A non-metallic element present in all living matter. Its release as *sulphur dioxide* during the combustion of *fossil fuels* is a precursor of *acid rain*.

**sulphur dioxide** An acid gas in which each *molecule* contains one *atom* of sulphur and two of *oxygen*. It is a product of the combustion of materials containing sulphur.

**sunspots** Dark spots that appear on the surface of the sun, associated with strong electromagnetic activity.

**supernova** A star which over a short period of a few days becomes exceptionally bright, and emits high levels of cosmic radiation, before declining again.

**supersonic transports (SSTs)** Commercial aircraft that routinely fly faster than the speed of sound, and at higher altitudes than subsonic airliners. Flying high in the *stratosphere,* they inject ozone destroying pollutants such as *oxides of nitrogen* and *odd hydrogens* directly into the *ozone* layer.

**sustainable development** Development which is both economically and environmentally sound, so that the needs of the world's current population can be met without jeopardizing those of future generations.

**Sustainable Development Commission** An institution established as a result of the *Earth Summit,* aimed at monitoring and promoting the approach towards *sustainable development* identified at the Summit.

**system** An assemblage of interrelated objects organized as an integrated whole. The earth/atmosphere system, for example, includes the various physical and biological components of the environment. These components are closely interrelated and work together for the benefit of all.

## T

**tall stacks policy** An approach to the problem of local air *pollution,* which involved the building of tall smokestacks to allow the release of pollutants outside the local atmospheric boundary layer. While this reduced local pollution, it introduced pollutants into the larger scale circulation and contributed to the *long range transportation of air pollution (LRTAP).*

**teleconnection** The linking of environmental events in time and place. The linkages usually involve a time-lag and include locations that may be wellseparated from each other. For example, an *El Niño* in the eastern Pacific late in one year may be linked to the failure of the Indian monsoon in the following year.

**temperature inversion** The reversal of the normal temperature decline with altitude in the *troposphere*. In an inversion, the temperature rises with altitude because of the presence of a layer of warm air above the cooler surface air.

**terpene** One of a group of *hydrocarbons* found in the essential oils of some plants, particularly conifers. Released from these plants, terpenes may be responsible for the haze common over such areas as the Blue Mountains of Virginia in the United States.

**terrestrial environment** That part of the environment that includes the components of the land surface—such as rock and soil—and the plants and animals that live on it.

**terrestrial radiation** Low energy, *long-wave radiation,* from the *infrared* sector of the spectrum, emitted by the earth's surface.

**thermal low** Low pressure system produced by the heating of the earth's surface and the air immediately above it. The process is particularly effective in areas of high *insolation.*

**thermonuclear device** A powerful bomb in which the explosive force is created by the fusion (combination) of the nuclei of hydrogen atoms—hence the name 'hydrogen bomb'.

**thermosphere** The outermost layer of the atmosphere beyond the *mesopause* some 80 km above the earth's surface.

**Third World** A term commonly applied to the developing and non-aligned nations of Africa, Asia and Latin America, to distinguish them from the 'western' nations of the 'first world' with their developed, capitalist economies, and the communist nations of the 'second world' with their centrally-planned economies.

**30 per cent club** A group of 21 nations—mainly from Europe, but including Canada—which agreed in 1985 to reduce trans-boundary emissions of sulphur dioxide by 30 per cent (of the 1980 level) by 1993, in an attempt to deal with the growing problem of *acid rain.*

**topsoil** The uppermost layer of the soil containing the bulk of its organic material, nutrients and living organisms.

**tornado** An intense rotating storm usually no more than 100 to 500 m in diameter, originating where cold and warm, moist air masses collide, and accompanied by winds that commonly exceed 200 kph.

**transient models** *General circulation models* which attempt to provide information at intermediate stages during the model run, unlike *equilibrium models* which provide only one final result.

**transpiration** The loss of water from vegetation to the atmosphere by its *evaporation* through leaf pores in individual plants.

**tree dieback** The gradual wasting of a tree from the outermost leaves and twigs inwards, leading to the death of the tree over several seasons. Dieback has been linked to the effects of *acid precipitation,* but there is no conclusive proof that this is the only factor involved. (See also *Waldsterben*.)

**triatomic oxygen** The gas *ozone,* in which each *molecule* consists of three *atoms* of *oxygen*.

**tropopause** The upper boundary of the *troposphere*. It varies in height from about 8 km at the poles to 16 km at the equator.

**troposphere** The lowest layer of the *atmosphere,* in which temperatures decrease with altitude at a rate of about 6.5°C per kilometre, to reach between-50°C and -60°C at the tropopause.

**TTAPS scenario** The scenario developed to explain the onset of *nuclear winter*. TTAPS is an acronym based on the first letters of the names of the scientists who developed the original hypothesis-Turco, Toon, Ackerman, Pollack and Sagan.

**Tu-144** A *supersonic transport* developed by Tupolev in the Soviet Union in the 1970s.

## U

**ultraviolet radiation** High energy, short-wave, *solar radiation,* most of which is absorbed by the *ozone* layer in the *stratosphere*. Thinning of the *ozone* layer has increased the proportion of ultraviolet radiation reaching the earth's surface, giving rise to fears of an increasing incidence of *skin cancer* and other radiation related problems.

**United Nations Conference on Desertification (UNCOD)** A conference held in Nairobi, Kenya in 1977 which established the modern approach to the problem of *desertification*.

**United Nations Conference on Environment and Development (UNCED)** An international conference—the *Earth Summit*—held in Rio de Janeiro, Brazil in 1992, with the theme of *sustainable development,* based on economically and environmentally sound principles. (See also *Agenda 21, Global Forum* and *Rio Declaration*.)

**United Nations Conference on the Human Environment (UNCHE)** Held in Stockholm, Sweden in 1972, this was the first conference to draw worldwide attention to the immensity of environmental problems, thus ushering in the modern era in environmental studies.

**United Nations Environment Program (UNEP)** A programme designed to combat the environmental damage caused by development projects in developing nations.

**upper westerlies** Westerly winds that blow in the upper atmosphere close to the *tropopause* in mid to high latitudes. (See also *jet streams* and *Rossby waves*.)

## V

**Villach Conference** The first of the major, modern environmental conferences to deal with the rising levels of *greenhouse gases* in the *atmosphere* and their impact on *climate,* held at Villach, Austria in 1985. It established an Advisory Group on Greenhouse Gases (AGGG) to ensure that the recommendations of the conference were followed up.

**visible light** Radiation from that part of the spectrum to which the human eye is sensitive. Visible light occupies a position between *ultraviolet* and *infrared radiation* in the spectrum and varies in colour, the shorter wavelengths being blue and the longer wavelengths red.

**vitamin D** The vitamin essential for the uptake of calcium by the human body. It is important for the proper growth and maintenance of bone, and insufficient vitamin D consumption can lead to rickets, a disease which causes bones to become prone to bending and fracturing.

**Volcanic Explosivity Index (VEI)** An index for comparing individual volcanic eruptions. It is based on volcanological criteria such as the intensity, dispersive power and destructive potential of the eruption, as well as the volume of material ejected. (See also *Dust Veil Index (DVI)* and *Glaciological Volcanic Index (GVI)*.)

## W

**Waldsterben** The destruction of the forests. A term coined in Germany to describe the damage caused to forests by *acid rain*. (See also *tree dieback*.)

**Walker circulation** A strong latitudinal circulation in the equatorial atmosphere which contrasts with the normal meridional circulation. It is particularly well marked in the Pacific Ocean where it is linked with the *Southern Oscillation*.

**water balance** A book-keeping approach to the moisture budget. It involves the comparison of moisture input *(precipitation)* and output *(evapotranspiration)* to provide a value for the net surplus or deficit of water at a specific location.

**weather** The current or short-term state of the *atmosphere* expressed in terms of such variables as temperature, precipitation, airflow and cloudiness.

**weather forecasting models** Models which use fundamental equations representing atmospheric process to predict short-term changes in meteorological elements.

**weather modification** Any change in weather conditions caused by human activity, whether by design or accident.

**weathering** The physical and chemical breakdown of rocks at the earth's surface, brought about by exposure to air, water, temperature change and organic activity.

**wet deposition** The most common form of *acid precipitation,* in which the acids are present in solution in the atmosphere and reach the earth's surface in rain, snow, hail and fog. (See also *dry deposition*.)

**windbreak** A row of trees or shrubs planted at right angles to the airflow. The consequent reduction in windspeed helps to protect sensitive plants, reduces the rate of *evapotranspiration* and helps to prevent *soil erosion*.

**World Commission on Environment and Development** A commission chaired by Gro Harlem Brundtland, the Norwegian Prime Minister, in 1987. It promoted the concept of *sustainable development,* and led directly to the *UNCED*.

**World Meteorological Organization (WMO)** A United Nations sponsored organization based in Geneva, Switzerland, which coordinates worldwide, weather data collection and analysis.

## X, Y, Z

**xerophytic vegetation** Plants adapted to life in arid conditions.

**zonal index** A measure of the intensity of the midlatitude atmospheric circulation pattern. During a period of high zonal index, the airflow is west to east or latitudinal. A low zonal index involves a south-north-south or meridional component as a result of waves forming in the airflow.

# Bibliography


Abrahamsen, G., Seip, H.M. and Semb, A. (1989) 'Long-term acidic precipitation studies in Norway', in D.C.Adriano and M.Havas, (eds) *Acidic Precipitation, Volume 1, Case Studies,* New York: Springer-Verlag.

Adetunji, J., McGregor, J. and Ong, C.K. (1979) 'Harmattan haze', *Weather* 34:430–6.

Ahrens, C.D. (1993) *Essentials of Meteorology,* Minneapolis/St. Paul: West Publishing Company.

Almer, B., Dickson, W., Ekstrom, C. and Hornstrom, E. (1974) 'Effects of acidification in Swedish lakes', *Ambio* 3:30–6.

Anon. (1983) 'One-third of German trees hit by acid rain', *New Scientist,* 100 (1381): 250.

——(1984) 'Balancing the risks: what do we know?', *Weatherwise* 37:240–9.

Anthes, R.A., Cahir, J.J., Fraser, A.B. and Panofsky, H.A. (1980) *The Atmosphere,* (3rd edition), Columbus, Ohio: Merrill.

Appleby, L. and Harrison, R.M. (1989) 'Environmental effects of nuclear war', *Chemistry in Britain,* 25:1223–8.

Arthur, L.M. (1988) *The Implication of Climate Change for Agriculture in the Prairie Provinces,* CCD 88–01, Ottawa: Atmospheric Environment Service.

Ashford, O.M. (1981) 'The dream and the fantasy', *Weather* 36:323–5

——(1992) 'Development of weather forecasting in Britain, 1900–40', *Weather* 47:394–402.

Austin, J. (1983) 'Krakatoa Sunsets', *Weather* 38: 226–31.

Bach, W. (1972) *Atmospheric Pollution,* New York: McGraw-Hill.

——(1976) 'Global air pollution and climatic change', *Reviews of Geophysics and Space Physics* 14: 429–74.

——(1979) 'Short-term climatic alterations caused by human activities: status and outlook', *Progress in Physical Geography* 3:55–83.

——(1986) 'Nuclear war: the effects of smoke and dust on weather and climate', *Progress in Physical Geography* 10:315–63.

Baker, J.P. and Schofield, C.L. (1985) 'Acidification impacts on fish populations: a review', in D.D. Adams and W.P.Page (eds) *Acid Deposition: Environmental, Economic and Political Issues,* New York: Plenum Press.

Balchin, W.G.V. (1964) 'Hydrology' in J.W.Watson and J.B.Sissons (eds) *The British Isles: A Systematic Geography,* London: Nelson.

Ball, T. (1986) 'Historical evidence and climatic implications of a shift in the boreal forest-tundra transition in Central Canada' , *Climatic Change,* 8: 121–34.

Balling, R.C. (1991) 'Impact of desertification on regional and global warming', *Bulletin of the American Meteorological Society* 72:232–4

Bark, L.D. (1978) 'History of American droughts', in N.J.Rosenberg (ed.) *North American Droughts,* Boulder, Colorado: Westview Press.

Barrie, L.A. (1986) 'Arctic air pollution: An overview of current knowledge', *Atmospheric Environment,* 20:643–63.

Barrie, L.A. and Hoff, R.H. (1985) 'Five years of air chemistry observations in the Canadian Arctic', *Atmospheric Environment,* 19:1995–2010.

Barry, R.G. and Chorley, R.J. (1992) *Atmosphere, Weather and Climate,* London: Routledge.

Barton, I.J., Prata, A.J., Watterson, I.G. and Young, S.A. (1992) 'Identification of the Mount Hudson volcanic cloud over S.E.Australia', *Geophysical Research Letters* 19:1211–14.

Berkofsky, L. (1986) 'Weather modification in arid regions: the Israeli experience', *Climatic Change* 9:103–12.

Bingemer, H.G. and Crutzen, P.J. (1987) 'The production of methane from solid wastes', *Journal of Geophysical Research* 92:2181–7.

Biswas, A.K. (1974) *Energy and the Environment,* Ottawa: Environment Canada.

Blake, D.R. and Rowland, F.S. (1988) 'Continuing worldwide increase in tropospheric methane', *Science* 239:1129–31.

Blank, L.W., Roberts, T.M. and Skeffington, R.A.

(1988) 'New perspectives on forest decline', *Nature,* 336:27–30.
Bolin, B. (1960) 'On the exchange of carbon dioxide between the atmosphere and the sea', *Tellus,* 12: 274–81.
——(1972) 'Atmospheric chemistry and environmental pollution', in D.P.Mclntyre (ed.) *Meteorological Challenges: A History,* Ottawa: Information Canada.
——(1986) 'How much $CO_2$ will remain in the atmosphere?', in B.Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds), *The Greenhouse Effect, Climate Change and Ecosystems,* SCOPE 29, New York: Wiley.
Bolin, B., Jager, J. and Doos, B.R. (1986) 'The greenhouse effect, climatic change, and ecosystems: a synthesis of present knowledge' in B. Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds) *The Greenhouse Effect, Climatic Change and Ecosystems,* SCOPE 29, New York: Wiley.
Bolle, H.J., Seiler, W. and Bolin, B. (1986) 'Other greenhouse gases and aerosols', in B.Bolin, B.R. Doos, J.Jager and R.A.Warrick (eds) *The Greenhouse Effect, Climatic Change and Ecosystems,* SCOPE 29, New York: Wiley.
Borchert, J.R. (1950) 'The climate of the central North American grassland', *Annals of the Association of American Geographers* 40:1–39.
Bowman, K.P. (1986) 'Interannual variability of total ozone during the breakdown of the Antarctic circumpolar vortex', *Geophysical Research Letters* 13:1193–6.
Bradley, R.S. and Jones, P.D. (1992) *Climate since A.D. 1500,* London: Routledge.
Brakke, D.F., Landers, D.H. and Eilers, J.M. (1988) 'Chemical and physical characteristics of lakes in the northeastern United States', *Environmental Science and Technology* 22:155–63.
Brasseur, G. and Granier, C. (1992) 'Mount Pinatubo aerosols, chlorofluorocarbons and ozone depletion', *Science* 257:1239–42.
Bretherton, P.P., Bryan, K. and Woods, J.D. (1990) Time-dependent greenhouse-gas-induced climate change' in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press.
Bruce, J. and Hengeveld, H.G. (1985) 'Our changing northern climate', *Geography* 14:1–6.
Bryson, R.A. (1968) 'All other factors being constant …; a reconciliation of several theories of climatic change', *Weather,* 21:56–61 and 94.
——(1973) 'Drought in the Sahel: who or what is to blame?', *Ecologist* 3:366–71.
Bryson, R.A. and Dittberner, G.J. (1976) 'A nonequilibrium model of hemispheric mean surface temperature', *Journal of Atmospheric Sciences* 33: 2094–106.
Bryson, R.A. and Murray, T.J. (1977) *Climates of Hunger,* Madison: University of Wisconsin Press.
Bryson, R.A. and Peterson, J.T. (1968) 'Atmospheric aerosols: increased concentrations during the past decades', *Science* 162:120–1.
Bryson, R.A., Lamb, H.H. and Donley, D.L. (1974) 'Drought and the decline of the Mycenae', *Antiquity* 48:46–50.
Burdett, N.A., Cooper, J.R.P., Dearnley, S., Kyte, W.S. and Turnicliffe, M.F. (1985) 'The application of direct limestone injection to U.K.power stations', *Journal of the Institute of Engineering,* 58:64–9.
Burroughs, W.J. (1981) 'Mount St. Helens: a review', *Weather* 36:238–40.
Butler, J.H., Elkins, J.W., Hall, B.D., Cummings, S.O. and Montzka, S.A. (1992) 'A decrease in the growth rates of atmospheric halon concentrations', *Nature* 359:403–5.
Calder, N. (1974) *The Weather Machine and the Threat of Ice,* London: BBC Publications.
Callaghan, T.V., Bacon, P.J., Lindley, D.K. and el Moghraby, A.I. (1985) 'The energy crisis in the Sudan: alternative supplies of biomass', *Biomass* 8:217–32.
Callendar, G.S. (1938) 'The artificial production of carbon dioxide and its influence on temperature', *Quarterly Journal of the Royal Meteorological Society* 64:223–37.
Callis, L.B. and Natarajan, M. (1986) 'Ozone and nitrogen dioxide changes in the stratosphere during 1979–1984', *Nature* 323:772–7.
CIDA (Canadian International Development Agency) (1985) *Food Crisis in Africa,* Hull, Quebec: CIDA.
Capot-Rey, R. (1951) 'Une carte de l'indice d'aridité au Sahara Français', *Bulletin de l'Association Géographique Francaise* 216/7:73–6.
Carpenter, R. (1968) *Discontinuity in Greek Civilization,* New York: W.W.Norton.
Catchpole, A.J.W. and Milton, D. (1976) 'Sunnier prairie cities—a benefit of natural gas', *Weather* 31:348–54.
Caulfield, C. and Pearce, F. (1984) 'Ministers reject clean-up of acid rain', *New Scientist* 104 (1433): 6.
Cess, R.D. and Potter, G.L. (1984) 'A commentary on the recent $CO_2$-climate controversy', *Climatic Change* 6:365–76.
Chapman, S. (1930) 'A theory of upper atmospheric ozone', *Quarterly Journal of the Royal Meteorological Society* 3:103.
Charles, D.F., Battarbee, R.W., Reuberg, I., VanDam, H. and Smot, J.P. (1990) 'Palaeoecological analysis of lake acidification trends in North America and Europe using diatoms and clirysophytes', in S.A.Norton, S.E.Lindberg and A.L. Page (eds)

*Acidic Precipitation, Volume 4, Soils, Aquatic Processes and Lake Acidification,* New York: Springer-Verlag.

Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Coakley, J.A., Hansen, J.E. and Hofmann, D.J. (1992) 'Climate forcing by anthropogenic aerosols', *Science* 255:423–30.

Charney, J. (1975) 'Dynamics of deserts and drought in the Sahel', *Quarterly Journal of the Royal Meteorological Society* 101:193–202.

Chase, A. (1988) 'The ozone precedent', *Outside* 13: 37–40.

Cheng, H.C., Steinberg, M. and Beller, M. (1986) *Effects of Energy Technology on Global $CO_2$ Emissions,* Washington, DC: US Department of Energy.

Chester, D.K. (1988) 'Volcanoes and climate: recent volcanological perspectives', *Progress in Physical Geography* 12:1–35.

Cho, H.R., Iribarne, J.V., Grabenstetter, J.E. and Tam, Y.T. (1984) 'Effects of cumulus cloud systems on the vertical distribution of air pollutants' in P.J.Samson (ed.) *The Meteorology of Acid Deposition,* Pittsburgh: Air Pollution Control Association.

Cicerone, R.J. and Oremland, R. (1988) 'Biogeochemical aspects of atmospheric methane', *Global Biogeochemical Cycles* 2:299–327.

Cicerone, R.J., Stolarski, R.S. and Walters, S. (1974) 'Stratospheric ozone destruction by man-made chlorofluoromethanes', *Science* 185:1165–7.

Clery, D. (1992) 'A climate of confidence', *New Scientist* 134 (1823): 12–13.

Climate Institute (1988a) 'NASA scientist testifies greenhouse warming has begun', *Climate Alert* 1: 1–2.

——(1988b) 'Is there a drought/greenhouse effect connection', *Climate Alert* 1:9.

——(1988c) 'CFC producers plan phaseout', *Climate Alert* 1:1.

——(1992a) 'Marshall Islands study measures to thwart ocean rise', *Climate Alert* 5:1 and 4.

——(1992b) 'Are we heading into an era of more intense hurricanes?', *Climate Alert* 5:1 and 6–7.

Cocks, A. and Kallend, T. (1988) 'The chemistry of atmospheric pollution' *Chemistry in Britain,* 24: 884–8.

Concar, D. (1992) 'The resistible rise of skin cancer', *New Scientist* 134 (1821): 23–8.

Cortese, T. (1986) 'The scientific and economic implications for acid rain control', in *Conference Proceedings: Intergovernmental Conference on Acid Rain. Quebec, April 10, 11 and 12, 1985,* Quebec City: Ministry of the Environment.

Crane, A. and Liss, P. (1985) 'Carbon dioxide, climate and the sea', *New Scientist* 108 (1483): 50–4.

Crawford, M. (1985) 'Sub-Sahara needs quick help to avert disaster', *Science* 230:788.

Critchfield, H.J. (1983) *General Climatology,* Englewood Cliffs: Prentice-Hall.

Cronan, C.S. and Schofield, C.L. (1979) 'Aluminum leaching response to acid precipitation: effects on high elevation watersheds in the north-east', *Science* 204:304–6.

Cronin, J.F. (1971) 'Recent volcanism and the stratosphere', *Science* 172:847–9.

Cross, M. (1985a) 'Africa's drought may last many years', *New Scientist* 105 (1439): 9.

——(1985b) 'Waiting, and hoping, for the big rains', *New Scientist* 105 (1443):3–4.

Crutzen, P.J. (1972) 'SSTs—A threat to the earth's ozone shield', *Ambio* 1:41–51.

——(1974) 'Estimates of possible variations in total ozone due to natural causes and human activities', *Ambio* 3:201–10.

Crutzen, P.J. and Arnold, F. (1986) 'Nitric acid cloud formation in the cold Antarctic stratosphere: a major cause for the springtime "ozone hole"', *Nature* 324:651–5.

Crutzen, P.J., Aselmann, I. and Seiler, W. (1986) 'Methane production by domestic animals, wild ruminants, other herbivorous fauna and humans', *Tellus* 38:271–84.

Cubasch, U. and Cess, R.D. (1990) 'Processes and modelling' in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press.

Cunningham, W.P. and Saigo, B.W. (1992) *Environmental Science: A Global Concern.* Dubuque, Iowa: W.C.Brown.

Delmas, R., Ascencio, J.M. and Legrand, M. (1980) 'Polar ice evidence that atmospheric $CO_2$ 20,000 yr B.P. was 50% of present', *Nature* 284:155–7.

Deshler, T., Adriani, A., Gobbi, G.P., Hofmann, D.J., Di Donfrancesco, G. and Johnson, B.J. (1992) 'Volcanic aerosol and ozone depletion within the Antarctic polar vortex during the austral spring of 1991', *Geophysical Research Letters* 19: 1819–22.

Detwyler, T.R. (ed.) (1971) *Man's Impact on Environment,* New York: McGraw-Hill.

di Sarra, A., Cacciani, M., Di Girolamo, P., Fiocco, G., Fua, D., Knudsen, B., Larsen, N. and Joergensen, J.S. (1992) 'Observations of correlated behaviour of stratospheric ozone and aerosol at Thule during winter 1991–1992', *Geophysical Research Letters* 19:1823–6.

Dickinson, R.E. (1986) 'How will climate change', in B.Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds), *The Greenhouse Effect, Climatic Change and Ecosystems, SCOPE 29,* New York: Wiley.

Dotto, L. and Schiff, H. (1978) *The Ozone War,* Garden City, New York: Doubleday.

Dutton, E.G. and Christy, J.R. (1992) 'Solar radiative forcing at selected locations and evidence for global lower stratosphere cooling following the eruptions of El Chichon and Pinatubo', *Geophysical Research Letters* 19:2313–16.

Dyer, A.J. and Hicks, B.B. (1965) 'Stratospheric transport of volcanic dust inferred from solar radiation measurements', *Nature* 94:545–54.

Eagleman, J.R. (1985) *Meteorology: The Atmosphere in Action,* Belmont, California: Wadsworth.

Edmonds, J.A., Reilly, J.M., Gardner, R.H. and Brenkert, A. (1986) *Uncertainty in Future Global Energy Use and Fossil Fuel* $CO_2$ *Emission: 1975 to 2075*, Washington, DC: US Department of Energy.

Ehrlich, P.R. *et al.* (1983) 'Long-term biological consequences of nuclear war', *Science* 222: 1293–1300.

Elkins, J.W., Thompson, T.M., Swanson, T.H., Butler, J.H., Hall, B.D., Cummings, S.O., Fisher, D.A. and Raffo, A.G. (1993) 'Decrease in the growth rates of atmospheric chlorofluorocarbons 11 and 12', *Nature* 364:780–3

Ellis, E.G., Zeldin, M.D., Brewer, R.L. and Shepard, L.S. (1984) 'Chemistry of winter type precipitation in southern California', in P.J.Samson (ed.) *The Meteorology of Acid Deposition,* Pittsburgh: Air Pollution Control Association.

Ellis, E.G., Erbes, R.E. and Grott, J.K. (1990) 'Abatement of atmospheric emissions in North America: progress to date and promise for the future' in S.E.Linberg, A.L.Page and S.A.Norton. (eds) *Acidic Precipitation, Volume 3, Sources, Deposition and Canopy Interactions,* New York: Springer-Verlag.

Ellis, H.T. and Pueschel, R.F. (1971) 'Solar radiation: absence of air pollution trends at Mauna Loa', *Science* 172:845–6.

Elwood, J.W. and Mulholland, P.J. (1989) 'Effects of acidic precipitation on stream ecosystems', in D.C. Adriano and A.H.Johnson, (eds) *Acidic Precipitation, Volume 2, Biological and Ecological Effects,* New York: Springer-Verlag.

Enhalt, D.H. (1980) 'The effects of chlorofluoromethanes on climate', in W.Bach, J.Pankrath and J.Williams (eds) *Interactions of Energy and Climate,* Dordrecht: Reidel.

Environment Canada (1986) *Understanding* $CO_2$ *and Climate—Annual Report 1985,* Ottawa: Atmospheric Environment Service.

——(1987) *Understanding* $CO_2$ *and Climate—Annual Report 1986,* Ottawa: Atmospheric Environment Service.

——(1989) *Preserving the Ozone Layer: a Step Beyond,* Ottawa: Commercial Chemicals Branch.

——(1991) *A Report on Canada's Progress toward a National Set of Environmental Indicators,* SOE Report No. 91–1, Ottawa: Environment Canada.

——(1992) *Stratospheric Ozone Depletion,* SOE Bulletin 92–1, Ottawa: State of the Environment Reporting.

——(1993) *State of the Environment Newsletter, No. 9,* Ottawa: State of the Environment Reporting.

Farman, J.C., Gardiner, B.C. and Shanklin, J.D. (1985) 'Large losses of total ozone in Antarctica reveal seasonal $ClO_x/NO_x$ interaction', *Nature* 315: 207–10.

Felch, R.E. (1978) 'Drought: characteristics and assessment', in N.J.Rosenberg (ed.) *North American Droughts,* Boulder, Colorado: Westview Press.

Fennelly, P.F. (1981) 'The origin and influence of airborne particulates', in B.J.Skinner (ed.) *Climates, Past and Present,* Los Altos, California: Kauffmann.

Fernandez, I.J. (1985) 'Acid deposition and forest soils: potential impacts and sensitivity', in D.D. Adams and W.P.Page (eds) *Acid Deposition: Environmental, Economic and Political Issues,* New York: Plenum Press.

Findley, R. (1981) 'The day the sky fell', *National Geographic* 159:50–65.

Fischer, W.H. (1967) 'Some atmospheric turbidity measurements in Antarctica', *Journal of Applied Meteorology* 6:958–9.

Flohn, H. (1980) *Possible Climatic Consequences of a Man-Made Global Warming RR-80–30,* Laxenburg, Austria: International Institute for Applied Systems Analysis.

Foley, H.M. and Ruderman, M.A. (1973) 'Stratospheric NO production from past nuclear explosions', *Journal of Geophysical Research* 78: 4441–50.

Folland, C.K., Palmer, T.N. and Parker, D.E. (1986) 'Sahel rainfall and worldwide sea temperatures 1901–85; observational, modelling, and simulation studies', *Nature,* 320:602–7.

Folland, C.K., Karl, T. and Vinnikov, K.Y. (1990) 'Observed climate variations and change', in J.T. Houghton, G.J.Jenkins and J.J.Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press

Forster, B.A. (1985) 'Economic impact of acid deposition in the Canadian aquatic sector', in D.D.Adams and W.P.Page (eds) *Acid Deposition: Environmental, Economic and Political Issues,* New York: Plenum Press.

Fowler, M.M. and Barr, S. (1984) 'A long range atmospheric tracer field test' in P.J.Samson (ed.)

*The Meteorology of Acid Deposition,* Pittsburgh: Air Pollution Control Association.
Fritts, H. (1965) 'Tree-ring evidence for climatic changes in western North America, *Monthly Weather Review* 93:421–43.
Gadd, A.J. (1992) 'Scientific statements and the Rio Earth Summit', *Weather* 47:294–315.
Garnett, A. (1967) 'Some climatological problems in urban geography with reference to air pollution', *Transactions of the Institute of British Geographers* 42:21–43.
Gates, W.L., Rowntree, P.R. and Zeng, Q-C. (1990) 'Validation of climate models' in J.D.Houghton, G.J.Jenkins and J.J.Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press
Glaeser, B. (1990) 'The environmental impact of economic development: problems and policies', in T.Cannon and A.Jenkins. (eds) *The Geography of contemporary China,* London: Routledge.
Glantz, M.H. (ed) (1977) *Desertification: Environmental Degradation in and around Arid Lands,* Boulder, Colorado: Westview Press.
Gobbi, G.P., Congeduti, F. and Adriani, A. (1992) 'Early stratospheric effects of the Pinatubo eruption', *Geophysical Research Letters* 19: 997–1000.
Goldman, M.I. (1971) 'Environmental disruption in the Soviet Union' in T.R.Detwyler (ed.) *Man's Impact on Environment,* New York: McGraw-Hill.
Gorham, C. and Gordon, A.G. (1960) 'The influence of smelter fumes upon the chemical composition of lake waters near Sudbury, Ontario and upon the surrounding vegetation', *The Canadian Journal of Botany* 38:477–87.
Green, C. (1992) 'Economics and the "Greenhouse Effect"', *Climatic Change* 22:265–91.
Green, O. and Salt, J. (1992) 'Limiting climate change: verifying national commitments', *Ecodecision* December: 9–13
Gribbin, J. (1978) 'Fossil fuel: future shock?', *New Scientist* 79 (1117):541–3.
——(1981) 'The politics of carbon dioxide', *New Scientist* 90 (1248):82–4.
——(1982) *Future Weather and the Greenhouse Effect,* New York: Delacorte.
——(1992) 'Arctic ozone threatened by greenhouse warming…and dust from last year's volcanoes', *New Scientist* 136 (1849):16.
——(1993) *The Hole in the Sky* (revised edition), New York: Bantam.
Groisman, P.Y. (1992) 'Possible regional climate consequences of the Pinatubo eruption: an empirical approach', *Geophysical Research Letters* 19:1603–6.
Grove, A.T. (1986) 'The state of Africa in the 1980s', *The Geographical Journal* 152:193–203.
Haas, P.M., Levy, M.A. and Parson, E.A. (1992) 'The Earth Summit—How should we judge UNCED's success?', *Environment* 34:7–11 and 26–33.
Haines, B.L. and Carlson, C.L. (1989) 'Effects of acid precipitation on trees', in D.C.Adriano and A.H. Johnson (eds) *Acidic Precipitation, Volume 2, Biological and Ecological Effects,* New York: Springer-Verlag.
Hameed, S. and Dignon, J. (1992) 'Global emissions of nitrogen and sulphuric oxides in fossil-fuel combustion', *Journal—Air and Waste Management Association,* 42:159–63.
Hamilton, R.A. and Archbold, J.W. (1945) 'Meteorology over Nigeria and adjacent territory', *Quarterly Journal of the Royal Meteorological Society* 71:231–62.
Hammond, A.L. and Maugh, T.H. (1974) 'Stratospheric pollution: Multiple threats to earth's ozone', *Science* 186:335–8.
Hampson, J. (1974) 'Photochemical war on the atmosphere', *Nature* 250:189–91.
Handel, M.D. and Risbey, J.S. (1992) 'An annotated bibliography on the greenhouse effect and climatic change', *Climatic Change* 21:97–255.
Hansen, J. and Lebedeff, S. (1988) 'Global surface air temperatures: update through 1987', *Geophysical Research Letters* 15:323–6.
Hansen, J.E., Lacis, A., Ruedy, R. and Sato, M. (1992) 'Potential climatic impact of Mount Pinatubo eruption', *Geophysical Research Letters* 19: 215–18.
Hare, F.K. (1973) 'The atmospheric environment of the Canadian North' , in D.H.Pimlott, K.M. Vincent and C.E.McKnight (eds) *Arctic Alternatives,* Ottawa: Canadian Arctic Resources Committee.
Hare, F.K. and Thomas, M.K. (1979) *Climate Canada,* Toronto: John Wiley.
Harvey, H.H. (1989) 'Effects of acidic precipitation on lake ecosystems', in D.C.Adriano and A.H. Johnson (eds), *Acidic Precipitation, Volume 2, Biological and Ecological Effects,* New York: Springer-Verlag.
Harwell, M.A. and Hutchinson, T.C. (1985) *Environmental Consequences of Nuclear War, Volume II: Ecological and Agricultural Effects, SCOPE 28,* New York: Wiley.
Hauhs, M. and Ulrich, B. (1989) 'Decline of European forests', *Nature* 339:265.
Havas, M. (1990) 'Recovery of acidified and metal contaminated lakes in Canada', in S.A.Norton, S.E.Lindberg and A.L.Page (eds) *Acidic Precipitation, Volume 4, Soils, Aquatic Processes and Lake Acidification.* New York: Springer-Verlag.

Hayashida, S. and Sasano, Y. (1993) 'Stratospheric aerosol change in the early stage of volcanic disturbance by the Pinatubo eruption observed over Tsukuba, Japan', *Geophysical Research Letters* 20(7): 575–8.

Heathcote, R.L. (1987) 'Images of a desert? Perceptions of arid Australia', *Australian Geographical Studies* 25:3–25.

Hekstra, G.P (1986) 'Will climatic changes flood the Netherlands? Effects on agriculture, land-use and well-being', *Ambio* 15:316–26.

Hekstra, G.P. and Liverman, D.M. (1986) 'Global food futures and desertification', *Climatic Change* 9: 59–66.

Henderson-Sellers, A. (1990) 'Greenhouse guessing: when should scientists speak out?', *Climatic Change* 16:5–8.

——(1991) 'Global climate change: the difficulties of assessing impacts', *Australian Geographical Studies* 29:202–25.

Hendrey, G.R. (1985) 'Acid deposition: a national problem', in D.D.Adams and W.P.Page (eds) *Acid Deposition: Environmental, Economic and Political Issues,* New York: Plenum Press.

Hengeveld, H.G. (1991) *Understanding Atmospheric Change,* SOE Report 91–2, Ottawa: Environment Canada.

Henriksen, A. and Brakke, D.F. (1988) 'Sulphate deposition to surface water', *Environmental Science and Technology* 22:8–14.

Hepting, G.H. (1971) 'Damage to forests from air pollution', in T.R.Detwyler (ed.) *Man's Impact on Environment,* New York: McGraw-Hill.

Hidore, J.J. and Oliver, J.E. (1993) *Climatology: An Atmospheric Science,* New York: Macmillan.

Hoffman, J.S., Keyes, D. and Titus, J.G. (1983) *Projecting Future Sea Level Rise,* US Environmental Protection Agency: Washington DC.

Houghton, J.T. (1992) 'Global warming: a 1992 update', *Ecodecision* June: 8–9.

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds) (1990) *Climate Change: The 1PCC Scientific Assessment,* Cambridge: Cambridge University Press.

Houghton, J.T., Callender, B.A. and Varney, S.K. (1992) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* Cambridge: Cambridge University Press.

Howard, R. and Perley, M. (1991) *Poisoned Skies,* Toronto: Stoddart.

Hulme, M. (1989) 'Is environmental degradation causing drought in the Sahel? An assessment from recent empirical research', *Geography* 74:38–46.

——(1993) 'Global warming', *Progress in Physical Geography* 17:81–91.

Hulme, M. and Kelly, M. (1993) 'Exploring the links between desertification and climate change', *Environment* 35:4–11 and 39–45.

Hunt, P. (1992) 'Putting Asian acid rain on the map', *New Scientist,* 136 (1851): 6.

Idso, S.B. (1980) 'The climatological significance of doubling of Earth's atmospheric carbon dioxide concentration' , *Science* 207:1462–3.

——(1981) 'Carbon dioxide—an alternative view', *New Scientist* 92 (1279):444–6.

——(1982) *Carbon Dioxide: Friend or Foe,* Tempe, Arizona: IBR Press.

——(1983) 'Do increases in atmospheric $CO_2$ have a cooling effect on surface air temperature?', *Climatological Bulletin* 17:22–6.

——(1987) 'A clarification of my position on the $CO_2$/climate connection', *Climatic Change* 10: 81–6.

IPCC (Intergovernmental Panel on Climate Change) (1991) *Climate Change: The IPCC Response Strategies,* Washington DC: Island Press.

Israelson, D. (1987) 'Acid rain update', *Toronto Star,* April 4, A1-A3.

Jacobsen, T. and Adams, R.M. (1971) 'Salt and silt in ancient Mesopotamian agriculture', in T.R. Detwyler (ed) *Man's Impact on Environment,* New York: McGraw-Hill.

Jeffries, D.S. (1990) 'Snowpack storage of pollutants, release during melting, and impact on receiving waters' , in S.A.Norton, S.E.Lindberg and A.L. Page (eds) *Acidic Precipitation, Volume 4, Soils, Aquatic Processes, and Lake Acidification,* New York: Springer-Verlag.

Jenkins, I. (1969) 'Increases in averages of sunshine in Greater London', *Weather* 24:52–4.

Jensen, K.W. and Snekvik, E. (1972) 'Low pH levels wipe out salmon and trout populations in southernmost Norway', *Ambio* 1:223–5.

Johnson, A.H. and Siccama, T.G. (1983) 'Acid deposition and forest decline', *Environmental Science and Technology* 17:294–305.

Johnson, A.H., Siccama, T.G., Silver, W.L. and Battles, J.J. (1989) 'Decline of red spruce in highelevation forests of New York and New England', in D.C.Adriano and M.Havas (eds) *Acidic Precipitation, Volume 1, Case Studies,* New York: Springer-Verlag.

Johnson, D.W., Kilsby, C.G., McKenna, D.S., Saunders, R.W., Jenkins, G.J., Smith, F.B. and Foot, J.S. (1991) 'Airborne observations of the physical and chemical characteristics of the Kuwait oil smoke plume', *Nature* 353:617–21.

Johnson, F.S. (1972) 'Ozone and SSTs', *Biological Conservation* 4:220–2.

Johnston, H.S. (1971) 'Reduction of stratospheric ozone by nitrogen oxide catalysts from SST exhaust', *Science* 173:517–22.

Jones, M.D.H. and Henderson-Sellers, A. (1990)

'History of the greenhouse effect', *Progress in Physical Geography* 14:1–18.
Kamara, S.I. (1986) 'The origins and types of rainfall in West Africa', *Weather* 41:48–56.
Karl, T.R. and Quayle, R.G. (1981) 'The 1980 summer heat and drought in historical perspective', *Monthly Weather Review* 109:2055.
Katz, R.W. and Glantz, M.H. (1977) 'Rainfall statistics, droughts and desertification in the Sahel', in M.H.Glantz (ed.) *Desertification: Environmental Degradation in and around Arid Lands* , Boulder, Colorado: Westview Press.
Keepin, W., Mintzer, I. and Kristoferson, L. (1986) 'Emission of $CO_2$ into the atmosphere', in B. Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds) *The Greenhouse Effect, Climatic Change and Ecosystems,* SCOPE 29, New York: Wiley.
Kellogg, W.W. (1980) 'Aerosols and climate', in W. Bach, J.Pankrath and J.Williams (eds), *Interactions of Energy and Climate,* Dordrecht: Reidel.
——(1987) 'Mankind's impact on climate: the evolution of an awareness', *Climatic Change* 10: 113–36.
Kellogg, W.W. and Schneider, S.H. (1977) 'Climate, desertification and human activities', in M.H. Glantz (ed.) *Desertification: Environmental Degradation in and around Arid Lands,* Boulder, Colorado: Westview Press.
Kemp, D.D. (1982) 'The drought of 1804–1805 in Central North America', *Weather* 37:34–40.
——(1991) 'The greenhouse effect: a Canadian perspective', *Geography* 76:121–31.
Kerr, J.B., Wardle, D.I. and Tarasick, D.W. (1993) 'Record low ozone values over Canada in early 1993', *Geophysical Research Letters* 20:1979–82.
Kerr, R.A. (1989) 'Greenhouse skeptic out in the cold', *Science* 246:1118–19.
Keys, J.G., Johnston, P.V., Blatherwick, R.D. and Murcray, F.J. (1993) 'Evidence for heterogeneous reactions in the Antarctic autumn stratosphere', *Nature* 361:49–51.
Kheshgi, H.S. and White, B.S. (1993) 'Does recent global warming suggest an enhanced greenhouse effect?', *Climatic Change* 22:121–39.
Kiernan, V. (1993) 'Atmospheric ozone hits a new low', *New Scientist* 138 (1871): 8.
Kleinbach, M.H. and Salvagin, C.E. (1986) *Energy Technologies and Conversion Systems,* Englewood Cliffs: Prentice Hall.
Komhyr, W.D., Grass, R.D. and Leonard, R.K. (1986) 'Total ozone decrease at the South Pole 1964–1985', *Geophysical Research Letters* 13: 1248–51.
Krug, E.G. and Frink, C.R. (1983) 'Acid rain in acid soil—a new perspective', *Science* 221:520–5.
Kyte, W.S. (1981) 'Some chemical and chemical engineering aspects of flue gas desulphurization', *Transactions of the Institution of Chemical Engineers* 59:219–29.
——(1986a) 'Some aspects of possible control technologies for coal-fired power stations in the United Kingdom', *Mine and Quarry* 15:26–9.
——(1986b) 'Possible emissions control technologies for coal-fired power stations—the United Kingdom', paper presented at the Institution of Chemical Engineers Conference on 'The Problem of Acid Emission' 22–23 September 1986: University of Birmingham.
——(1988) 'A programme for reducing $SO_2$ emissions from U.K.power stations—present and future', *CEGB: Corporate Environment Unit:* Paper 1–2.
LaBastille, A. (1981) 'Acid rain—how great a menace?', *National Geographic* 160:652–81.
Lacis, A., Hansen J. and Sato, M. (1992) 'Climate forcing by stratospheric aerosols', *Geophysical Research Letters* 19:1607–10.
Lamb, H.H. (1970) 'Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance', *Philosophical Transactions of the Royal Society,* A 266:435–533.
——(1972) *Climate: Present, Past and Future; Volume I, Fundamentals and Climate Now,* London: Methuen.
——(1977) *Climate: Present, Past and Future: Volume 2, Climatic History and the Future,* London: Methuen.
Landsberg, H.H. (1986) 'Potentialities and limitations of conventional climatological data for desertification monitoring and control', *Climatic Change* 9:123–8.
Last, F.T. (1989) 'Acidic deposition: case study Scotland', in D.C.Adriano and M.Havas (eds) *Acidic Precipitation, Volume 1, Case Studies,* New York: Springer-Verlag.
Last, F.T. and Nicholson, I.A. (1982) 'Acid rain', *Biologist* 29:250–2.
Lawson, M.P. and Stockton, C. (1981) 'The desert myth evaluated in the context of climatic change', in C.D.Smith and M.Parry (eds) *Consequences of Climatic Change,* Nottingham: University of Nottingham.
Le Houerou, H.N. (1977) 'The nature and causes of desertization', in M.H.Glantz (ed.) *Desertification: Environmental Degradation in and around Arid Lands,* Boulder, Colorado: Westview Press.
Leggett, J. (1992) 'Running down to Rio', *New Scientist* 134 (1819):38–42. Legrand, M. and Delmas, R.J. (1987) 'A 220-year continuous record of volcanic $H_2SO_4$ in the Antarctic ice sheet', *Nature* 327:671–6.
Leighton, P.A. (1966) 'Geographical aspects of air pollution', *Geographical Review* 56:151–74.

Lemonick, M.D. (1987) 'The heat is on', *Time* 130: 62–75.
Levenson, T. (1989) *Ice Time: Climate, Science and Life on Earth,* New York: Harper & Row.
Lippmann, M. (1986) 'The effects of inhaled acid on human health', in *Conference Proceedings: Intergovernmental Conference on Acid Rain, Quebec, April 10, 11 and 12, 1985,* Quebec City: Ministry of the Environment.
Lockwood, J.G. (1979) *Causes of Climate,* London: Edward Arnold.
——(1984) 'The Southern Oscillation and El Niño', *Progress in Physical Geography* 8:102–10.
——(1986) 'The causes of drought with particular reference to the Sahel', *Progress in Physical Geography* 10:110–19.
Lourenz, R.S. and Abe, K. (1983) 'A dust storm over Melbourne', *Weather* 38:272–4.
Lovelock, J.E. (1972) 'Gaia as seen through the atmosphere', *Atmospheric Environment* 6:579–80.
——(1986) 'Gaia: the world as living organism', *New Scientist* 112 (1539):25–8.
Lovelock, J.E. and Epton, S. (1975) 'The quest for Gaia', *New Scientist* 65 (939):304–6.
Lovelock, J.E. and Margulis, L. (1973) 'Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis', *Tellus* 26:2.
Ludlum, D.M. (1971) *Weather Record Book,* Princeton, New Jersey: Weatherwise Inc.
Lutgens, F.K. and Tarbuck, E.J. (1982) *The Atmosphere,* Englewood Cliffs: Prentice-Hall.
McCarthey, J.J., Brewer, P.G. and Feldman, G. (1986) 'Global ocean flux', *Oceanus* 29:16–26.
McCormick, M.P. (1992) 'Initial assessment of the stratospheric and climatic impact of the 1991 Mount Pinatubo eruption', *Geophysical Research Letters* 19:49.
McCormick, R.A. and Ludwig, J.L. (1967) 'Climate modification by atmospheric aerosols', *Science* 156:1358–9.
MacCracken, M.C. and Luther, F.M. (1985a) *Detecting the Climatic Effects of Increasing Carbon Dioxide,* Washington, DC: US Department of Energy.
MacCracken, M.C. and Luther, F.M. (1985b) *Projecting the Climatic Effects of Increasing Carbon Dioxide,* Washington, DC: US Department of Energy.
Mackay, G.A. and Hengeveld, H.G. (1990) 'The changing atmosphere', in C.Mungall and D.J. MacLaren (eds) *Planet under Stress,* Toronto: Oxford University Press.
McKay, G.A., Maybank, J., Mooney, O.R. and Pelton, W.L. (1967) *The Agricultural Climate of Saskatchewan: Climatological Studies, No. 10,* Toronto: Canada, Dept of Transport, Meteorological Branch.
MacKenzie, D. (1987a) 'Ethiopia plunges towards another famine' *New Scientist* 115 (1573):26.
——(1987b) 'Can Ethiopia be saved?', *New Scientist* 115 (1579):54–8.
——(1992) 'Agreement reduces damage to ozone layer', *New Scientist* 136 (1850):10.
Mackie, R., Hunter, J.A.A., Aitchison, T.C., Hole, D., McLaren, K., Rankin, R., Blessing, K., Evans, A.T., Hutcheon, A.W., Jones, D.H., Soutar, D.S., Watson, A.C.H., Cornbleet, M.A. and Smith, J.F. (1992) 'Cutaneous malignant melanoma, Scotland 1979–89.', *The Lancet* 339:971–5.
Maddox, J. (1984) 'Nuclear winter not yet established', *Nature* 308:11.
Manabe, S. and Wetherald, R.T. (1975) 'The effects of doubling the $CO_2$ concentration on the climate of a general circulation model', *Journal of Atmospheric Science,* 32:3–15.
Manabe, S. and Wetherald, R.T. (1986) 'Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide', *Science* 232:626–8.
Manabe, S., Wetherald, R.T. and Stouffer, R.J. (1981) 'Summer dryness due to an increase of atmospheric $CO_2$ concentration', *Climatic Change* 3:347–86
Marcus, A.A. and Rands, G.P. (1992) 'Changing perspectives on the environment', in R.A. Buchholz, A.A.Marcus and J.E. Post (eds) *Managing Environmental Issues: A Casebook,* Englewood Cliffs: Prentice-Hall.
Martec, Ltd (1987) *Effects of a One metre Rise in Sea Level at St. John, New Brunswick and the Lower Reaches of the St. John River CCD 87–04*, Ottawa: Atmospheric Environment Service.
de Martonne, E. (1926) 'Une nouvelle fonction climatologique: l'indice d'aridité', *Météorologie* 2: 449–59.
Mason, B.J. (1990) 'Acid rain—cause and consequence', *Weather* 45:70–9.
Meinl, H., Bach, W., Jager, J., Jung, H.J., Knottenberg, H., Marr, G., Santer, B.D. and Schwieren, G. (1984) *The Socio-Economic Impacts of Climatic Changes due to a Doubling of Atmospheric* $CO_2$ *Content,* Brussels: Commission of European Communities Report.
Meko, D.M. (1992) 'Dendroclimatic evidence from the Great Plains of the United States', in R.S. Bradley and P.D.Jones (eds) *Climate since AD 1500,* London: Routledge.
Melillo, J.M., Callaghan, T.V., Woodward, F.I., Salati, E. and Sinha, S.K. (1990) 'Effects of ecosystems', in J.T.Houghton, G.J.Jenkins and J.J.Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press.

Miller, J.M. (1984) 'Acid rain', *Weatherwise* 37: 234–9.
Miller, M. (1992) 'Getting grounded at Rio', *Ecodecision* June: 55–7.
Mintzer, I.M. (1992) 'National energy strategies and the greenhouse problem', in L.Rosen and R. Glasser (eds) *Climate Change and Energy Policy,* New York: American Institute of Physics.
Mitchell, J.F.B. (1983) 'The seasonal response of a general circulation model to changes in $CO_2$ and sea temperature', *Quarterly Journal of the Royal Meteorological Society* 109:113–52.
Mitchell, J.F.B., Manabe, S., Tokioka, T. and Meleshko, V. (1990) 'Equilibrium climate change', in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press.
Mitchell, J.M. (1970) 'A preliminary evaluation of atmospheric pollution as a cause of global temperature fluctuations of the past century', in S.F.Singer (ed.) *Global Effects of Environmental Pollution,* Dordrecht: Reidel.
——(1975) 'A reassessment of atmospheric pollution as a cause of long-term changes of global temperature', in S.F.Singer (ed.) *The Changing Global Environment,* Boston: Reidel.
Molina, M.J. and Rowland, F.S. (1974) 'Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone', *Nature* 249: 810–12.
Mooley, D.A. and Parthasarathy, B. (1983) 'Indian summer monsoon and El Niño', *Pure and Applied Geophysics* 121:339–52.
Moore, B. and Bolin, B. (1986) 'The oceans, carbon dioxide and global climate change', *Oceanus* 29: 9–15.
Morales, C. (1986) 'The airborne transport of Saharan dust: a review', *Climatic Change* 9:219–42.
More, R.J. (1969) 'Water and crops', in R.J.Chorley (ed.) *Water, Earth and Man,* London: Methuen.
Mortimer, M. (1989) *Adapting to Drought: Farmers, Famines and Desertification in West Africa,* Cambridge: Cambridge University Press.
Mossop, S.C. (1964) 'Volcanic dust collected at an altitude of 20 km', *Nature* 203:824–7.
Murphey, R. (1973) *The Scope of Geography,* Chicago: Rand McNally.
Musk, L. (1983) 'Outlook-changeable', *Geographical Magazine* 55:532–3.
NCGCC (1990) *An Assessment of the Impact of Climate Change Caused by Human Activities on China's Environment,* Beijing: National Coordinating Group on Climate Change.
Nelson, R. (1990) *Dryland management: the 'desertification' problem, World Bank Technical Paper No. 16,* Washington DC: World Bank.
Newell, R.E. and Dopplick, T.G. (1979) 'Questions concerning the possible influence of anthropogenic $CO_2$ on atmospheric temperature', *Journal of Applied Meteorology* 18:822–5.
Newhall, G.G. and Self, S. (1982) 'The volcanic explosivity index (VEI): an estimate of the explosive magnitude for historical volcanism', *Journal of Geophysical Research* 87:1231–8.
Nicholson, S.E. (1981) 'The historical climatology of Africa', in T.M.L.Wigley, M.J.Ingram and G. Farmer (eds) *Climate and History,* Cambridge: Cambridge University Press.
——(1989) 'Long-term changes in African rainfall', *Weather* 44:47–56.
Norton, P. (1985) 'Decline and Fall', *Harrowsmith* 9: 24–43.
NRC (National Research Council) (1982) *Carbon Dioxide and Climate: A Second Assessment.* Washington, DC: National Academy Press.
——(1983) *Changing Climate,* Washington, DC: National Academy Press.
Oguntoyinbo, J. (1986) 'Drought prediction', *Climatic Change* 9:79–90.
Okada, K., Ikegami, M., Uchino, O., Nikaidou, Y., Zaizen, Y., Tsutsumi, Y. and Makino, Y. (1992) 'Extremely high proportions of soot particles in the upper troposphere over Japan', *Geophysical Research Letters* 19:921–4.
Ontario: Ministry of the Environment (1980) *The Case Against the Rain,* Toronto: Information Services Branch, Ministry of the Environment.
Owen, J.A. and Ward, M.N. (1989) 'Forecasting Sahel rainfall', *Weather* 44:57–64.
Palmer, W.C. (1965) *Meteorological Drought,* Research Paper 45, Washington DC: US Weather Bureau.
Palutikof, J.P. (1986) 'Drought strategies in East Africa: the climatologist's role', *Climatic Change* 9:67–78.
Park, C.C. (1987) *Acid Rain: Rhetoric and Reality,* London: Methuen.
——(1991) 'Trans-frontier air pollution: some geographical issues' *Geography* 76:21–35.
Parry, M.L. (1978) *Climatic Change, Agriculture and Settlement,* Folkestone: Dawson.
Parson, E.A., Hass, P.M. and Levy, M.A. (1992) 'A summary of the major documents signed at the earth summit and the global forum', *Environment* 34:12–15 and 34–6.
Pearce, F. (1982a) 'Warning cones hoisted as acid rain-clouds gather', *New Scientist* 94 (1311):828.
——(1982b) 'Science and politics don't mix at acid rain debate', *New Scientist 95* (1312):3.

——(1982c) 'It's an acid wind that blows nobody any good', *New Scientist* 95 (1313):80.

——(1982d) 'The menace of acid rain', *New Scientist* 95 (1318):419–23.

——(1984) 'MPs back curbs on acid rain', *New Scientist* 103(1420)*:3*.

——(1990) 'Whatever happened to acid rain?', *New Scientist* 124 (1736):57–60.

——(199la) 'Desert fires cast a shadow over Asia', *New Scientist* 129 (1754):30–1.

——(1991b) 'A sea change in the Sahel', *New Scientist* 130 (1757):31–2.

——(1992a) 'Last chance to save the planet', *New Scientist* 134 (1823):24–8.

——(1992b) 'Despondency descends on Rio', *New Scientist* 134 (1824):4.

——(1992c) 'How green was our summit', *New Scientist* 134 (1827):12–13.

——(1992d) 'Grain yields tumble in a greenhouse world', *New Scientist* 134 (1817):4.

——(1992e) 'Will Britain fail the acid test?', *New Scientist* 136 (1850):11.

——(1992f) 'Miracle of the Shifting Sands', *New Scientist* 136 (1851):38–42.

Pégorié, J. (1990) 'On-farm agroforestry research: case study from Kenya's semi-arid zone', *Agroforestry Today* 2*:*4–7.

Peterson, J.T. and Junge, C.E. (1971) 'Sources of particulate matter in the atmosphere', in W.H. Matthews, W.W.Kellogg and G.D.Robinson (eds) *Man's Impact on the Climate,* Cambridge, Mass.: M.I.T.Press.

Phillips, D.W. (1982) *Climatic Anomalies and Unusual Weather in Canada during 1981,* Downsview, Ontario: Atmospheric Environment Service.

Piette, J. (1986) 'Les initiatives des provinces de l'Est du Canada en matiere de precipitations acides' in *Conference Proceedings: Intergovernmental Conference on Acid Rain. Quebec, April 10, 11 and 12, 1985,* Quebec City: Ministry of the Environment.

Pisias, N.G. and Imbrie, J. (1986) 'Variations in the earth's orbit influenced past climate changes', *Oceanus* 29*:*43–9.

Pitelka, L.F. and Raynal, D.J. (1989) 'Forest decline and acidic precipitation', *Ecology* 70:2–10.

Pittock, A.B. and Salinger, M.J. (1982) 'Towards regional scenarios for a $CO_2$-warmed earth', *Climatic Change,* 4:23–40.

Pittock, A.B. and Salinger, M.J. (1991) 'Southern hemisphere climate scenarios', *Climatic Change* 18:205–22

Pollack, J.B. and Ackerman, T.P. (1983) 'Possible effects of the El Chichón volcanic cloud on the radiation budget of the northern tropics', *Geophysical Research Letters* 10:1057–60.

Ponte, L. (1976) *The Cooling,* Englewood Cliffs: Prentice-Hall.

Porcella, D.B., Schefield, C.L., Depinto, J.V., Driscoll, C.T., Bukaveckas, P.A., Gloss, S.P. and Young, T.C. (1990) 'Mitigation of acidic conditions in lakes and streams' in S.A.Norton, S.E.Lindberg and A.L.Page (eds) *Acidic Precipitation, Volume 4, Soils, Aquatic Processes and Lake Acidification,* New York: Springer-Verlag.

Pueschel, R.F., Blake, D.F., Snetsinger, K.G., Hansen, A.D.A., Verma, S. and Kato, K. (1992) 'Black carbon (soot) aerosol in the lower stratosphere and upper troposphere', *Geophysical Research Letters* 19:1659–62.

Pyle, J. (1991) 'Closing in on Arctic ozone', *New Scientist* 132 (1794):49–52.

Quinn, W.H. and Neal, V.T. (1992) 'The historical record of El Niño events', in R.S.Bradley and P.D. Jones (eds) *Climate since AD 1500,* London: Routledge.

Ramage, J. (1983) *Energy: A Guidebook,* Oxford: Oxford University Press.

Ramanathan, V. (1975) 'Greenhouse effect due to chlorofluorocarbons: climatic implications', *Science* 190*:*50–1.

——(1988) 'The greenhouse theory of climate change: a test by inadvertent global experiment', *Science* 240*:*293–9.

Ramanathan, V., Callis, L.B. and Boughner, R.E. (1976) 'Sensitivity of surface temperature and atmospheric temperature to perturbations in the stratospheric concentration of ozone and nitrogen dioxide', *Journal of Atmospheric Science* 33: 1092–1112.

Ramanathan, V., Pitcher, G.J., Malone, R.C. and Blackmon, M.L. (1983) 'The response of a spectral GCM to refinements in radiative processes', *journal of Atmospheric Science* 40: 605–30.

Ramanathan, V., Singh, H.B., Cicerone, R.J. and Kiehl, J.T. (1985) 'Trace gas trends and their potential role in climate change', *Journal of Geophysical Research* 90:5547–56.

Rampino, M.R. and Self, S. (1984) 'The atmospheric effects of El Chichón', *Scientific American* 250: 48–57.

Rasmusson, E.M. and Hall, J.M. (1983) 'El Niño', *Weatherwise* 36:166–75.

Revelle, R. and Seuss, H.E. (1957) 'Carbon dioxide exchange between the atmosphere and ocean and the question of an increase of atmospheric $CO_2$ during the past decades', *Tellus* 9:18–27.

Ridley, M. (1993) 'Cleaning up with cheap technology', *New Scientist* 137 (1857):26–7.

Riefler, R.F. (1978) 'Drought: an economic perspective', in N.J.Rosenberg (ed.) *North*

*American Droughts,* Boulder, Colorado: Westview Press.

Roberts, L. (1989) 'Global warming: blaming the sun', *Science* 246:992–3.

Robitaille, L. (1986) 'Le déperissement des érablières au Québec; problématique et état des recherches', in *Conference Proceedings: Intergovernmental Conference on Acid Rain. Quebec, April 10, 11 and 12, 1985,* Quebec City: Ministry of the Environment.

Robock, A. (1981) 'A latitudinally dependent volcanic dust veil index and its effect on climate simulations', *Journal of Vulcanological and Geothermal Research* 11:67–80.

Rodriguez, J.M. (1993) 'Probing atmospheric ozone', *Science* 261*:*1128–9.

Rosen, J.M., Kjome, N.T. and Fast, H. (1992) 'Penetration of Mt. Pinatubo aerosols into the north polar vortex', *Geophysical Research Letters* 19:1751–4.

Rosenberg, N.J. (ed.) (1978) *North American Droughts,* Boulder, Colorado: Westview Press.

Rosenthal, H. and Wilson, J.S. (1987) *An Updated Bibliography (1945–1986) on Ozone, its Biological Effects and Technical Applications,* Halifax, Nova Scotia: Ministry of Supply and Services Canada.

Rowntree, P.R. (1990) 'Estimates of future climate change over Britain', *Weather* 45*:*38–42.

Ruderman, M.A. (1974) 'Possible consequences of nearby supernova explosions for atmospheric ozone and terrestrial life', *Science* 184:1079–81.

Sage, B. (1980) 'Acid drops from fossil fuels', *New Scientist* 85 (1197):743–5.

Salinger, M.J. and Pittock, A.B. (1991) 'Climate scenarios for 2010 and 2050 AD Australia and New Zealand', *Climatic Change* 18:259–69.

Sanders, D.W. (1986) 'Desertification processes and impact in rainfed agricultural regions', *Climatic Change* 9*:*33–42.

Sanderson, M. (1987) *Implications of Climatic Change for Navigation and Power Generation in the Great Lakes, CCD 87–03,* Ottawa: Atmospheric Environment Service.

Santer, B. (1985) 'The use of general circulation models in climate impact analysis—a preliminary study of the impact of $CO_2$-induced climatic change on West European agriculture', *Climatic Change* 1:71–93.

SCEP (1970) *Man's Impact on the Global Environment; Study of Critical Environmental Problems,* Cambridge, Mass.: M.I.T.Press.

Scheider, W., Adamski, J. and Paylor, M. (1975) *Reclamation of Acidified Lakes near Sudbury, Ontario,* Toronto: Ontario: Ministry of the Environment.

Schindler, D.W. and Bayley, S.E. (1990) 'Fresh waters in cycle', in C.Mungall and D.J.McLaren (eds) *Planet under Stress,* Toronto: Oxford University Press.

Schneider, S.H. (1978) 'Forecasting future droughts: is it possible?', in N.J.Rosenberg (ed) *North American Droughts,* Boulder, Colorado: Westview Press.

——(1986) 'A goddess of the earth?: the debate on the Gaia hypothesis—an editorial', *Climatic Changed:* 1–4.

——(1987) 'Climatic modeling', *Scientific American* 256*:*72–89.

Schneider, S.H. and Mass, C. (1975) 'Volcanic dust, sunspots and temperature trends', *Science* 190: 741–6.

Schneider, S.H. and Mesirow, L. (1976) *The Genesis Strategy,* New York: Plenum Press.

Schneider, S.H. and Thompson, S.L. (1981) 'Atmospheric $CO_2$ and climate: importance of the transient response', *Journal of Geophysical Research* 86:3135–47.

Schoeberl, M.R. and Kreuger, A.J. (1986) 'Overview of the Antarctic ozone depletion issue', *Geophysical Research Letters* 13:1191–2.

SCOPE-ENUWAR (1987) 'Environmental consequences of nuclear war: an update', *Environment* 29:4–5 and 45.

Seager, J. (1991) 'Operation Desert Disaster', *Ecodecision* September: 42–6.

Seckmeyer, G. and McKenzie, R.L. (1992) 'Increased ultraviolet radiation in New Zealand (45°S) relative to Germany (48°N), *Nature* 359:135.

Sellers, W.D. (1973) 'A new global climatic model', *Journal of Applied Meteorology* 12:241–54.

Semazzi, F.H.M., Melita, V, and Sud, Y.C. (1988) 'An investigation of the relationship between sub-Saharan rainfall and global sea-surface temperatures', *Atmosphere-Ocean* 26:118–38.

Shaw, G.E. (1980) 'Arctic Haze', *Weatherwise* 33: 219–21.

Shaw, R.W. (1987) 'Air pollution by particles', *Scientific American* 257:96–103.

Shaw, W.S. (1992) 'Smoke at Bahrain during the Kuwaiti oil fires', *Weather* 47:220–6

Shine, K. (1988) 'Antarctic Ozone—An extended meeting report', *Weather* 43*:*208–10.

Shine, K., Derwent, R.G., Wuebbles, D.J. and Morcrette J.J. (1990) 'Radiative forcing of climate', in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press

Shriner, D.S. and Johnston, J.W. (1985) 'Acid rain interactions with leaf surfaces: a review', in D.D. Adams and W.P.Page (eds) *Acid Deposition: Environmental, Economic and Political Issues,* New York: Plenum Press.

Shugart, H.H., Antonovsky, P.G., Jarvis, P.G. and Sandford, A.P. (1986) '$CO_2$, climatic change and forest ecosystems' in B.Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds), *The Greenhouse Effect, Climatic Change and Ecosystems,* SCOPE 29, New York: Wiley.

Siegenthaler, U. (1984) '19th century measurements of atmospheric $CO_2$—a comment', *Climatic Change,* 6:409–11.

Simons, P. (1992) 'Why global warming could take Britain by storm' , *New Scientist* 136 (1846): 35–8.

Singer, S.F. (1984) 'Is the "nuclear winter" real?', *Nature* 310:625.

Singh, B. (1988) *The Implications of Climate Change for Natural Resources in Quebec, CCD 88–08,* Ottawa: Atmospheric Environment Service.

Slade, D.H. (1990) 'A survey of informed opinion regarding the nature and reality of "Global Greenhouse Warming"', *Climatic Change* 16:1–4.

SMIC (1971) *Inadvertent Climate Modification; Report of the Study of Man's Impact on Climate,* Cambridge, Mass.: M.I.T.Press.

Smit, B. (1987) *Implications of Climatic Change on Agriculture in Ontario CCD 87–02,* Ottawa: Atmospheric Environment Service.

Smith, J.W. (1920) 'Rainfall of the Great Plains in relation to cultivation', *Annals of the Association of American Geographers* 10:69–74.

Smith, T.M. and Shugart, H.H. (1993) 'The transient response of terrestrial carbon storage to a perturbed climate', *Nature* 361:523–6.

Smith, Z.A. (1992) *The Environmental Policy Paradox,* Englewood Cliffs: Prentice-Hall.

Spry, I.M. (1963) *The Palliser Expedition,* Toronto: Macmillan.

Starr, V.P. (1956) 'The general circulation of the atmosphere', *Scientific American* 195:40–5.

Steila, D. (1976) *The Geography of Soils,* Englewood Cliffs: Prentice-Hall.

Stevenson, A.C. (1993) 'Environmental acidification: a review of surface water acidification during 1991', *Progress in Physical Geography* 17:69–75.

Stewart, J. and Tiessen, H. (1990) 'Grasslands into deserts?', in C.Mungall and D.J.McLaren (eds) *Planet under Stress,* Toronto: Oxford University Press.

Stokes, P.M., Howell, E.T. and Krantzberg, G. (1989) 'Effects of acidic precipitation on the biota of freshwater lakes', in D.C.Adriano and A.H. Johnson (eds) *Acidic Precipitation, Volume 2, Biological and Ecological Effects,* New York: Springer-Verlag.

Stokoe, P. (1988) *Socio-economic Assessment of the Physical and Ecological Impacts of Climate Change on the Marine Environment of the Atlantic Region of Canada—Phase I CCD 88–07,* Ottawa: Atmospheric Environment Service.

Stolarski, R.S. and Cicerone R.J. (1974) 'Stratospheric chlorine. Possible sink for ozone', *Canadian journal of Chemistry* 52:1610–15.

Stolarski, R.S., Krueger, A.J., Schoeberl, M.R., McPeters, R.D., Newman, P.A. and Alpert, J.C. (1986) 'Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease', *Nature* 322: 808–11.

Strain, B.R. and Cure, J.D. (eds) (1985) *Direct Effects of Increasing Carbon Dioxide on Vegetation,* Washington, DC: US Department of Energy.

Stuiver, M. (1987) 'Atmospheric carbon dioxide and carbon reservoir changes', *Science* 199:253–8.

Sveinbjornsson, B. (1984) 'Alaskan plants and atmospheric carbon dioxide' in J.H.McBeath (ed.), *The Potential Effects of Carbon Dioxide—Induced Climatic Change in Alaska,* Conference Proceedings, Fairbanks: School of Agriculture and Land Resources Management, University of Alaska.

Sweeney, J. (1985) 'The 1984 drought on the Canadian prairies', *Weather* 40:302–9.

Swift, J. (1977) 'Pastoral development in Somalia: herding cooperatives as a strategy against desertification and famine', in M.H.Glantz (ed.) *Desertification: Environmental Degradation in and around Arid Lands,* Boulder, Colorado: Westview Press.

Taylor, N.K. (1992) 'The role of the ocean in the global carbon cycle', *Weather* 47:146–50 (Part 1) and 47:237–41 (Part 2).

Tegart, W.J., Sheldon, G.W. and Griffiths, D.C. (1990) *Climate Change: The IPCC Impacts Assessment,* Canberra: Australian Government Publishing Service.

Teller, E. (1984) 'Widespread after-effects of nuclear war', *Nature* 310:621–4.

Thackrey, T.O. (1971) 'Pittsburgh: how one city did it', in R.Revelle, A.Khosla and M.Vinovskis (eds) *The Survival Equation,* Boston: Houghton Mifflin.

Thomas, G. and Henderson-Sellers, A. (1987) 'Evaluation of satellite derived land cover characteristics for global climate warming', *Climatic Change* 11:313–47.

Thompson, S.L. and Schneider, S.H. (1986) 'Nuclear winter reappraised', *Foreign Affairs* 64: 981–1005.

Thornthwaite, C.W. (1931) 'The climate of North America according to a new classification', *Geographical Review* 21, 633–55.

——(1947) 'Climate and moisture conservation', *Annals of the Association of American Geographers* 37:87–100.

——(1948) 'An approach towards a rational classification of climate', *Geographical Review* 38: 55–94.

Thornton, F.C., Schaedle, M. and Raynal, D.J. (1986) 'Effect of aluminum on the growth of sugar maple in solution culture', *Canadian Journal of Forest Research* 16:892–6.

Tickell, O. (1992) 'Fire-fighters find gas that's easy on ozone', *New Scientist* 134 (1818):19.

Titus, J.G. (1986) 'Greenhouse effect, sea level rise and coastal zone management', *Coastal Zone Management Journal* 14:147–72.

Tomlinson, G.H. (1985) 'Forest vulnerability and the cumulative effects of acid deposition' in D.D. Adams and W.P.Page (eds) *Acid Deposition-Environmental Economic and Political Issues,* New York: Plenum Press.

Toon, O.B. and Pollack, J.B. (1981) 'Atmospheric aerosols and climate', in B.J.Skinner (ed.) *Climates Past and Present,* Los Altos, California: Kauffmann.

Toro, T. (1992) 'German industry freezes out green fridge', *New Scientist* 135 (1835):16.

Trewartha, G.T. and Horn, L.H. (1980) *An Introduction to Climate,* New York: McGraw-Hill.

Tucker, A. (1987) 'Ozone hole culprit pin-pointed', *Manchester Guardian Weekly* 137 (8):4.

Tullett, M.T. (1984) 'Saharan dust-fall in Northern Ireland', *Weather* 39:151–2.

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B. and Sagan, C. (1983) 'Nuclear winter: global consequences of multiple nuclear explosions', *Science 222:*1283–92.

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B. and Sagan, C. (1990) 'Climate and smoke: an appraisal of nuclear winter', *Science* 247:166–76.

Turk, J. (1980) *Introduction to Environmental Studies,* Philadelphia: Saunders.

Turk, J. and Turk, A. (1988) *Environmental Science,* Philadelphia: Saunders.

Ulrich, B. (1983) 'A concept of forest ecosystem stability and of acid deposition as driving force for destabilization', in B.Ulrich and J.Pankrath (eds) *Effects of Accumulation of Air Pollutants in Forest Ecosystems,* Dordrecht, Netherlands: Reidel.

——(1989) 'Effects of acidic precipitation on forest ecosystems in Europe' in D.C.Adriano and A.H.Johnson (eds) *Acidic Precipitation, Volume 2, Biological and Ecological Effects,* New York: Springer-Verlag.

Ulrich, B., Mayer, R. and Khanna, T.K. (1980) 'Chemical changes due to acid precipitation in a loess-derived soil in central Europe', *Soil Science* 130:193–9.

Valerie, K., Delers, A., Bruck, C., Thiriart, C., Rosenberg, H., Debouck, C. and Rosenberg, M. (1988) 'Activation of human immunodeficiency virus type 1 by DNA damage in human cells', *Nature* 333:78–81.

Van Cleve, K., Oliver, L., Schleuther, R., Viereck, L.A. and Dyrness, C.T. (1983) 'Productivity and nutrient cycling in taiga forest eco-systems', *Canadian Journal of Forest Resources* 13:747–66.

Van Kooten, G.C., Arthur, L. and Wilson, W.R. (1992) 'Potential to sequester carbon in Canadian forests: some economic considerations', *Canadian Public Policy* 18*:*127–38.

Van Royen, W. (1937) 'Prehistoric droughts in the central Great Plains', *Geographical Review* 27: 637–50.

van Ypersele, J.P. and Verstraete, M.M. (1986) 'Climate and desertification—editorial', *Climatic Change* 9*:*1–4.

Verstraete, M.M. (1986) 'Defining desertification: a review', *Climatic Change* 9*:*5–18.

Viereck, L.A. and Van Cleve, K. (1984) 'Same aspects of vegetation and temperature relationships in the Alaska Taiga', in J.H.McBeath (ed.) *The Potential Effects of Carbon Dioxide-Induced Climatic Change in Alaska,* Conference Proceedings, Fairbanks: School of Agriculture and Land Resources Management, University of Alaska.

Ware, H. (1977) 'Desertification and Population: Sub-Saharan Africa', in M.H.Glantz (ed.) *Desertification: Environmental Degradation in and around Arid Lands,* Boulder, Colorado: Westview Press.

Warren, A. and Agnew, C. (1988) *An Assessment of Desertification and Land Degradation in Arid and Semi-arid Areas,* London: Ecology and Conservation Unit, University College.

Warrick, R.A. (1993) 'Slowing global warming and sealevel rise: the rough road from Rio', *Transactions of the Institute of British Geographers* NS 18:140–8.

Warrick, R.A. and Oerlemans, H. (1990) 'Sea level rise' , in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds), *Climate Change: The IPCC Scientific Assessment,* Cambridge: Cambridge University Press.

Washington, W.M. and Parkinson, C.L. (1986) *An Introduction to Three Dimensional Climate Modeling,* Mill Valley, California: University Science Books.

Waterstone, M. (1993) 'Adrift in a sea of platitudes. Why we will not resolve the greenhouse issue', *Environmental Management*17:141–52.

Watson, J.W. (1963) *North America: Its Countries and Regions,* London: Longman.

Watson, R.T., Rodhe, H., Oeschger, H. and Siegenthaler, U. (1990) 'Greenhouse gases and aerosols', in J.T.Houghton, G.J.Jenkins and J.J. Ephraums (eds), *Climate Change: The IPCC*

*Scientific Assessment,* Cambridge: Cambridge University Press.

Webb, R.S. and Overpeck, J.T. (1993) 'Carbon reserves released?', *Nature* 361:497–8.

Webster, M. (1988) 'Queries and quandries' *Harrowsmith* 80:115–16.

Webster, P.J. (1984) 'The carbon dioxide/climate controversy: some personal comments on two recent publications', *Climatic Change* 6:377–90.

Weiss, H., Courty, M.A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R. and Curnow, A. (1993) 'The genesis and collapse of Third Millenium north Mesopotamian civilization', *Science* 261: 995–1004.

Wheaton, E.E., Singh, T., Dempster, R., Higginbotham, K.O., Thorpe, J.P., Van Kooten, G.C. and Taylor, J.S. (1989) *An Exploration and Assessment of the Implications of Climate Change for the Boreal Forest and Forestry Economics of the Prairie Provinces and Northwest Territories: phase one, CCD 89–02,* Ottawa: Atmospheric Environment Service.

Wigley, T.M.L. and Barnett, T.P. (1990) 'Detection of the greenhouse effect in the observations', in J.T.Houghton, G.J.Jenkins and J.J.Ephraums (eds), *Climate Change: The IPCC Scientific Assessment ,* Cambridge: Cambridge University Press.

Wigley, T.M.L., Jones, P.D. and Kelly, P.M. (1986) 'Empirical climate studies' in B.Bolin, B.R.Doos, J.Jager and R.A.Warrick (eds) *The Greenhouse Effect, Climatic Change and Ecosystems* SCOPE 29, New York: Wiley.

Williams, G.D.V., Fantley, R.A., Jones, K.H., Stewart, R.B. and Wheaton, E.E. (1988) *Estimating Effects of Climatic Change on Agriculture in Saskatchewan CCD 88–06,* Ottawa: Atmospheric Environment Service.

Williamson, S.J. (1973) *Fundamentals of Air Pollution,* Reading, Mass.: Addison-Wesley.

Wilson, A.T. (1978) 'Pioneer agricultural explosion of $CO_2$ levels in the atmosphere', *Nature* 273: 40–1.

Wilson, C.A. and Mitchell, J.F.B. (1987) 'Simulated climate and $CO_2$-induced climate change over western Europe', *Climatic Change* 10:11–42.

Wittwer, S. (1984) 'The rising level of atmospheric carbon dioxide: an agricultural perspective' in J.H. McBeath (ed.) *The Potential Effects of Carbon Dioxide-Induced Climatic Change in Alaska,* Conference Proceedings, Fairbanks: School of Agriculture and Land Resources Management, University of Alaska.

Wofsy, S.C., McElroy, M.B. and Sze, N.D. (1975) 'Freon consumption: implications for atmospheric ozone', *Science* 187:535–7.

World Resources Institute (1992) *World Resources: 1992–93 A Guide to the Global Environment,* New York: Oxford University Press.

# Index