CLIMATE CHANGE AND HUMAN HEALTH

An assessment prepared by a Task Group
on behalf of the World Health Organization, the World Meteorological
Organization and the United Nations Environment Programme

Editors:

A.J. McMichael, A. Haines, R. Slooff and S. Kovats.

Task Group Members:

M. Ando, Japan
R. Carcavallo, Argentina
P.R. Epstein, United States of America
A. Haines, United Kingdom
G. Jendritzky, Germany
L.S. Kalkstein, United States of America
A.J. McMichael, United Kingdom
R.A. Odongo, Kenya
J. Patz, United States of America
W.T. Piver, United States of America
R. Slooff, World Health Organization

WHO
World Health Organization
Geneva
1996

Contents

Preface

Carbon dioxide and other "greenhouse gases" are accumulating in the atmosphere as a result of human activities. The Intergovernmental Panel on Climate Change predicts that if this process continues, the resulting shifts in the composition of the atmosphere will lead to changes in the functioning of the world's climate system, with potentially serious consequences for humanity. Recent increases in temperature and changes in climate variability in numerous parts of the world are suspected by many scientists to be the first signals of such global climate change. The physical and ecological impacts of these changes could widely affect the quality of life. For instance, rising sea levels, more frequent droughts and heat waves, increased production of temperature-dependent air pollutants, and stresses on agricultural systems, could all affect human population health adversely. Indeed, recent global and regional climate events may have contributed to some of the increases observed in the incidence of new and recurrent infectious diseases. But our baseline scientific knowledge and our methods for assessing such health hazards are limited and need further development. Moreover, current climate forecasting models are relatively imprecise.

A precautionary approach to this human-made "greenhouse problem" could be adopted. This would entail an international effort to reduce and stabilize global emissions of greenhouse gases at levels whereby minimal climate change ensued. This in turn would necessitate a major shift in industrial and agricultural practices. How such a shift could be achieved is currently the subject of ongoing negotiations between national governments working within the UN Framework Convention on Climate Change.

The stakes are high on all sides. Some argue that future benefits of uncertain magnitude do not provide sufficient justification for investing in the mitigation measures advocated by the Convention, particularly since these measures could result in substantial economic losses. They insist that more research is needed and that major decisions should be postponed until the impacts of climate change can be predicted with more certainty. Those in favour of the Convention argue that the current cost of climate disturbances is mounting, that further damage to the systems that support human life may become irreversible, and that the cost of implementing adaptive measures in future — as opposed to taking preventive measures now — would be prohibitive.

This book, prepared jointly by the World Health Organization, the World Meteorological Organization and the United Nations Environment Programme, covers the subject of climate change to the full extent possible, given current scientific knowledge. It is intended to assist and promote further international collaboration aimed at improving our understanding of how climate variability and climate change affect human health, so that clear priorities can be established and preventive and protective action taken.

Hiroshi Nakajima, M.D, Ph.D
Director-General
World Health Organization

G.O.P. Obasi, D.Sc., L.L.D, O.F.R.
Secretary-General
World Meteorological Organization

Elizabeth Dowdeswell
Executive Director
United Nations Environment Programme

About this book

The potential health implications of climate change were first addressed by WHO in 1990 with the publication of a short document, *Potential health effects of climate change* (WHO/PEP/90.10), prepared with assistance from WMO. The assessment presented in this book was initiated after consultations that took place in 1993 between representatives of WHO, WMO and UNEP, several lead authors of the Intergovernmental Panel on Climate Change (IPCC) and staff of the United States Environmental Protection Agency (USEPA). These consultations revealed an urgent need for a broader study, based on IPCC's newer scenarios and predictions.

With seed money received from the USEPA, and very efficient working support rendered by the IPCC, it was possible — within a very short period of time — to establish a Task Group of diverse experts to work on this project, and to also serve as lead authors for the chapter on human population health in the *Second assessment report* of IPCC (Working Group II). Simultaneously, a small support office was established within the Environmental Health programme of WHO supported by a Steering Committee composed of WHO, WMO and UNEP staff members. The Task Group met three times in three years. Two subsequent draft texts were produced and circulated within the three collaborating agencies, and among several IPCC lead authors and other experts affiliated to various environmental health research institutions and meteorological services worldwide. An editorial group selected from Task Group members in the UK, together with the WHO coordinator, undertook the final process of integrating and incorporating the various comments received, and provided support for the work of the WHO language editor.

In addition to the USEPA grant, the project received substantial financial support from the Dutch government (specifically the Ministries of Development Cooperation, Environment, and Health and Welfare) and the IPCC, and from the regular budgets of UNEP, WMO and WHO. Without these generous contributions the task could not have been achieved.

The authors would like to offer special thanks to the many individuals who supplied data or text, reviewed early drafts, or provided assistance in other ways, thereby contributing much to the monograph's present substance. The authors owe special thanks to:

For significant text contributions: Dr J. Almendares, Medical School UNAH, Tegucigalpa, Honduras; Dr S. Curto de Casas, Centro de Investigaciónes Biometeorológicas, Buenos Aires, Argentina; Dr I. Galíndez Girón, University Los Andes, Trujillo, Venezuela; Mr W.J.M. Martens, Department of Mathematics, University of Limburg, Maastricht, the Netherlands; Ms A.R. Moreno MSc, Pan American Center for Human Ecology and Health, PAHO, Metepec, Mexico; Dr R.J. Nicholls, Flood Hazard Research Centre, Middlesex University, London, UK; Dr W.K. Reisen, School of Public Health, University of California, Berkeley, USA; Ms E. McNamara, Infoterra, USEPA Library, Washington DC, USA; Ms D. Mills, Center for Climate Research, University of Delaware, Newark, USA; Professor K.R. Smith, Center for Occupational and Environmental Health, University of California, Berkeley, USA.

For other valuable text contributions: Professor H.R. Anderson, St George's Medical School, London, UK; Professor D.J. Bradley, London School of Hygiene and Tropical Medicine, London, UK; Dr J. Balbus, George Washington University School of Medicine and Health Sciences, Washington DC, USA; Dr M.N. Kyule, Department of Public Health and Epidemiology, University of Nairobi, Kenya; Professor R. La Porte, Graduate School of Public Health, University of Pittsburgh, USA; Professor D. Waltner-Toews, Population Medicine Department, University of Guelph, Guelph, Canada.

For substantial review comments: Dr B. Armstrong, Australian Institute of Health and Welfare, Canberra, Australia; Dr R. Berkleman, National Center for Infectious Diseases, Atlanta, USA; Dr A. Brazel, Department of Geography, Arizona State University, Tempe, USA; Mr C. Corvalán, WHO, Geneva; Dr U. Cubasch, Deutsches Klimarechenzentrum, Hamburg, Germany; Dr D.M. DeMarini, Environmental Carcinogenesis Division, US Environmental Protection Agency, Research Triangle Park, USA; Dr P. Dolin, International Centre for Eye Health, London, UK; Dr P. Ekins, Birkbeck College, London, UK; Dr J. Fouts, National Institute of Environmental Health Sciences, Research Triangle Park, USA; Professor G. Gettinby, Department of Statistics and Modelling Science, University of Strathclyde, Glasgow, UK; Dr H.N.B. Gopalan, UNEP, Nairobi, Kenya; Dr C. Green, Flood Hazard Research Centre, Middlesex University, London, UK; Dr D. Gubler, Division of Vector-Borne Diseases, CDC, Fort Collins, USA; Dr S. Hales, Department of Public Health, Wellington School of Medicine, Wellington, New Zealand; Dr A. Hall, London School of Hygiene and Tropical Medicine, London, UK; Professor G. Johnson, Institute of Ophthalmology, London, UK; Dr E.M. Kilbourne, Epidemiology Program Office, Centers for Disease Control, Atlanta, USA; Dr T. Kjellström, WHO, Geneva; Mr R.J.T. Klein, School of Environmental Sciences, University of East Anglia, Norwich, UK; Dr M.L. Kripke, MD Anderson Cancer Center, University of Texas, Houston, USA; Dr Lal, Indian Institute of Technology, New Delhi, India; Professor J. Last, University of Ottawa, Ottawa, Canada; Dr R. Leemans, National Institute of Public Health and Environmental Protection, Bilthoven, the Netherlands; Dr L. Levins, Harvard School of Public Health, Boston, USA; Dr T. Munn, Institute of Environmental Studies, Toronto, Canada; Mr L.E. Olsson, WMO, Geneva; Dr J. Reilly, US Department of Agriculture, Economic Research Service, Washington DC, USA; Dr D.J. Rogers, Department of Zoology, University of Oxford, Oxford, UK; Professor J. Samet, School of Hygiene and Public Health, Johns Hopkins University, Baltimore, USA; Mr R. Schmidt, WHO, Geneva; Professor C.D. Schoenwiese, Institut für Meteorologie und Geophysik, Frankfurt, Germany; Dr D. Viner, Climatic Research Unit, University of East Anglia, UK; Professor S.K. West, Dana Center for Preventive Ophthalmology, Johns Hopkins School of Medicine and Public Health, Baltimore, USA; Dr K. Western, National Institute for Allergy and Infectious Diseases, Bethesda, USA; Professor A. Woodward, Department of Public Health, Wellington School of Medicine, Wellington, New Zealand.

A number of research groups and university departments worldwide have made significant contributions to this study in the form of information, permission to use data, or staff time spent on the preparation of text or reviews. This support is gratefully acknowledged. These institutions cannot be listed here, but a special word of thanks is due to the London School of Hygiene and Tropical Medicine, London, UK, for having facilitated and supported this project to an extent far beyond the terms of reference of its working agreement with WHO. Finally, the authors wish to thank Ms J. Sawyer, language editor at WHO, for her important contribution to this book.

Abbreviations and acronyms

AMOEBE	algemene methode voor oecosysteembeschrijving en beoordeling (Dutch: general method for the description and evaluation of ecosystems)
ASP	amnesic shellfish poisoning
BCC	basal cell carcinoma
BCG	Bacillus of Calmette and Guerin vaccine (against tuberculosis)
BMA	British Medical Association
CCIRG	Climate Change Impacts Review Group, UK
CDC	Centers for Disease Control and Prevention, USA
CFC	chlorofluorocarbon
CGCP	Canadian Global Change Program
CISET	Committee on Science, Environment and Technology (US National Science and Technology Committee)
CSM	cerebrospinal meningitis
DHF	dengue haemorrhagic fever
DSP	diarrhoeic shellfish poisoning
DSS	dengue shock syndrome
ECHAM	European Centre/Hamburg Model (European Centre for Medium-Range Weather Forecasts/MPI)
EEE	eastern equine encephalitis
ENSO	El Niño/Southern Oscillation
EPPO	European and Mediterranean Plant Protection Organization
FAO	Food and Agriculture Organization of the United Nations
GAW	Global Atmosphere Watch (WMO)
GCM	general circulation model
GCOS	Global Climate Observing System (ICSU/IOC/UNEP/WMO)
GEMS	Global Environmental Monitoring System (UNEP/WHO)
GFDL	Geophysical Fluid Dynamics Laboratory, USA
GHG	greenhouse gas
GIEWS	Global Information and Early Warning System (FAO)
GIS	geographic information system
GISS	Goddard Institute of Space Studies, USA
GLOSS	Global Sea Level Observing System (IOC)
GNP	gross national product
GOOS	Global Ocean Observing System (IOC)
GTOS	Global Terrestrial Observing System (FAO/ICSU/UNEP/UNESCO/WMO)
GVA	global vulnerability assessment
HCFC	hydrochlorofluorocarbon
HIV/AIDS	human immunodeficiency virus/acquired immunodeficiency syndrome
IARC	International Agency for Research on Cancer
ICDDR	International Centre for Diarrhoeal Disease Research, Bangladesh
ICSU	International Council of Scientific Unions
IDNDR	International Decade for Natural Disaster Reduction
IFRC	International Federation of the Red Cross and Red Crescent Societies
IGBP	International Geosphere–Biosphere Programme (ICSU)

IHDP	International Human Dimensions of Global Environmental Change Programme (ICSU/ISSC)
IOC	Intergovernmental Oceanographic Commission of UNESCO
IOM	Institute of Medicine, USA
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
ISSC	International Social Science Council
LAIA	Lung and Asthma Information Agency, UK
MOVE	model for vegetation impacts
MPI	Max-Planck Institute für Meteorologie, Germany
NASA	National Aeronautics and Space Administration, USA
NCI	National Cancer Institute, USA
NDVI	normalized difference vegetation index
NHMRC	National Health and Medical Research Council, Australia
NMSC	non-melanotic skin cancer
NOAA	National Oceanic and Atmospheric Administration, USA
OECD	Organisation for Economic Co-operation and Development
PAHO	Pan American Health Organization
PM	particulate matter
ProMED	Program for Monitoring Emerging Diseases (Federation of American Scientists)
PSP	paralytic shellfish poisoning
PTSD	post-traumatic stress disorder
RMSF	Rocky Mountain spotted fever
SCC	squamous cell carcinoma
SLE	St Louis encephalitis
SPOT	Systeme pour l'Observation de la Terre (France)
TOGA	Tropical Oceans and the Global Atmosphere (part of the World Climate Research Programme)
UKMO	United Kingdom Meteorological Office
UKTR	United Kingdom Meteorological Office Transient Experiment
UNCED	United Nations Conference on Environment and Development (1992)
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
UV-A	ultraviolet A radiation
UV-B	ultraviolet B radiation
UV-C	ultraviolet C radiation
UVR	ultraviolet radiation
WCED	World Commission on Environment and Development
WEE	western equine encephalitis
WHO	World Health Organization
WMO	World Meteorological Organization
WSI	weather stress index
WWW	World Weather Watch (WMO)

Units of measurement

E	exa (10^{18})
G	giga (10^{9})
k	kilo (10^{3})
m	milli (10^{-3})
µ	micro (10^{-6})
n	nano (10^{-9})
DU	Dobson unit (2.69×10^{19} molecules/cm^2)
g	gram
GtC	gigatonnes of carbon
J	joule
kWh	kilowatt-hour
mb	millibar
mmt	million tonnes
mph	miles per hour
ppmv	parts per million (10^{6}) by volume
ppbv	parts per billion (10^{9}) by volume
pptv	parts per trillion (10^{12}) by volume
W	watt

Executive summary

As climatologists become more certain of the likelihood of human-induced global climate change, so questions about its possible consequences command increasing attention. In particular, it is now recognized that climate change, by altering local weather patterns and by disturbing life-supporting natural systems and processes, would affect the health of human populations. The range of health effects would be diverse, often unpredictable in magnitude, and sometimes slow to emerge. Adverse effects are likely to outweigh beneficial effects substantially.

The debate about global climate change is as unusual as it is controversial. Scientific arguments usually concern interpretation of evidence gathered from the present or from the past, rather than the forecasting of complex future changes. For example, when epidemiologists argue about the effect of air pollution on asthma, they do so with reference to existing empirical research results. However, forecasting the health impacts of climate change requires us to undertake scenario-based risk assessment — that is, to apply our knowledge of environment–health relationships gained from limited past experience to future environmental changes of which we are uncertain and that will probably far exceed the range of past variation. For example, the rate of global temperature increase that the Intergovernmental Panel on Climate Change (IPCC) has forecast for the next century is much faster than any that has occurred in the past 10 000 years. The resultant uncertainties in forecasting health impacts are compounded by uncertainties concerning social, demographic, economic and technological changes that may influence human vulnerability or adaptive capacity.

This, then, is clearly not an "exact science". But the range and seriousness of the potential health impacts of climate change means that the risk assessments discussed in this volume constitute a very important scientific undertaking. A large part of the task entails considering the various indirect effects upon human health arising from climatic stresses upon the stability and productivity of ecological systems. With few exceptions, the causal relationships involved are complex and multifactorial. A premise underlying this volume, therefore, is that we must now think carefully, and within an ecological framework, about the longer-term implications for human health of disturbing or damaging components of the biosphere.

Chapter 1 describes the historical and economic context within which the climate change issue has arisen and discusses the scale, complexity and fundamental "newness" of the problem. An up-to-date review of the science of greenhouse gas accumulation and its effects upon the climate system is given in Chapter 2. Based on anticipated future trends in greenhouse gas emissions, the IPCC estimates that global mean temperature will have risen by 1–3.5°C by late next century. Chapter 2 also discusses the associated problem of stratospheric ozone depletion. Recent studies indicate that warming of the lower atmosphere may, via stratospheric cooling, exacerbate ozone depletion.

The various possible impacts of climate change and stratospheric ozone depletion upon human health are examined in Chapters 3 to 8. The impacts are referred to as "direct" or "indirect". Whereas some impacts can be foreseen easily — such as an increase in deaths due to an increase in the frequency and severity of heat waves — others would depend on, for example, changes in patterns of mosquito populations and regional food production and are therefore less easy to predict. Other, more diverse and diffuse public health impacts would result from population displacement and conflict following sea level rise, and disruption of local economic activity and employment. In particular, these chapters examine:

- *The potential adverse health impacts of summertime heat stress, the ameliorative effects of milder winters upon cold-related mortality, and the likely increased production of particular air pollutants and aeroallergens due to meteorological factors.* Current models indicate that, by around 2050, many major cities could be experiencing up to several thousand extra heat-related deaths annually, independent of any increase due to population growth.

- *The complex ways in which climatic changes would affect the potential transmission of vector-borne diseases (such as malaria, dengue, various other haemorrhagic viruses and schistosomiasis), and the likely increased occurrence of waterborne and foodborne infections.* Recent mathematical models suggest that by 2100 climate change could have increased substantially the proportion of the world's population living in potential malaria transmission zones.

- *The potential impacts of climate change upon agricultural productivity.* While temperature increases and soil moisture changes, and shifts in patterns of plant pests and diseases, could lead to decreases in agricultural productivity, carbon dioxide fertilization could lead to some increases in agricultural productivity. Regional variations in gains and losses would probably result in a slight overall decrease in world cereal grain productivity. Decreases would be most likely in regions that are already food-insecure. The potential effects of changes in ocean temperatures, ocean currents, nutrient flows and surface winds upon aquatic productivity are discussed with particular reference to the simultaneous impacts of human activities on the health of coastal ecosystems.

- *Possible changes in extreme weather events, such as heat waves, floods, storms and droughts, and how these would affect human health.* Although uncertain about the specific and local effects of climate change, climatologists anticipate regional increases in the frequency of droughts, and in heavy precipitation events (leading to increased flooding). Health effects could include not only greater risk of death, injury and starvation, particularly among vulnerable Third World populations, but also increased incidence of psychological and social disorders.

- *The impacts of sea level rise on the health of vulnerable populations.* These impacts would include displacement, loss of agricultural land and some fisheries, freshwater salinization, and social disruption, all of which could affect health status adversely. Specific health hazards could arise from heightened storm surges and from damage to coastal infrastructure (including waste-water and sanitation systems, housing and roads).

- *Potential health effects of increased ground-level exposure to ultraviolet radiation (UVR).* Increased UVR levels due to stratospheric ozone depletion have become evident in recent years, particularly at mid and high latitudes. If sustained over several decades, these levels will lead to increased rates of skin cancer (especially the non-melanoma cancers) in light-skinned populations, and probably also to increased incidence of eye cataracts, and possibly to suppression of the body's immune system. Additionally, increased UVR levels could have adverse effects on biomass production, and hence on human food production, although the magnitude of such effects is uncertain.

Chapters 9 and 10 address the implications of global climate change for research, monitoring and social-policy response. We must foster interdisciplinary research and techniques adapted for the modelling of complex processes and the reasonable handling of attendant uncertainties. Human health-related indices should be developed and incorporated into local, regional and global monitoring systems. These indices would embrace environmental signals (such as weatherwatch indices, insect population densities and crop production), shifts in the ranges or densities of sensitive indicator species (such as rodents and phytoplankton) and explicit changes in human vulnerability to disease (such as poorer nutritional status, UVR-induced tissue damage and altered infectious disease incidence).

The sustainability of human population health is, of course, a fundamentally important criterion of successful social and economic policy. As such it is an essential component of sustainable development as expressed in *Agenda 21*, adopted at the United Nations Conference on Environment and Development in 1992. While there can as yet be few certainties in forecasts of the future health effects of climate change, the role of science in this context must be to assist adoption of precautionary policies that balance current social needs against serious, perhaps unacceptable, future risks.

Chapter 1

Introduction

Context and background

We are living at a remarkable moment in the history of the human species. Human population size, and the extent and nature of our economic activities are now so great that the gaseous composition of the lower and middle atmospheres (the troposphere and the stratosphere) has begun to change. This is likely to affect the world's climate, many other of the world's natural systems, ground-level exposure to ultraviolet radiation (UVR), and indeed, all life on earth.

Rapid increases this century in world energy production (through combustion of fossil fuels and biomass) and in world food production (through animal husbandry, irrigated agriculture and forest clearance) have caused heat-trapping "greenhouse gases" (GHGs) to accumulate in the troposphere. This, say climatologists, will change the world's climate, most probably at a much greater rate than has ever been experienced by human societies since the advent — approximately 10 000 years ago — of agriculture and settled living. Some climatologists also believe that the unusual weather patterns of the past two decades may signal the beginning of a longer-term process of change in average temperature, precipitation and patterns of extreme weather events. Such "climate change" could have a wide range of impacts on human health, most of which would probably be adverse.

Meanwhile, a separate process has resulted in the accumulation of certain human-made gases in the stratosphere, where they destroy ozone. These gases derive, in particular, from the widespread use of various halocarbons for refrigeration, insulated packaging, and in industry and agriculture. The main consequence of this stratospheric ozone depletion is reduced shielding of Earth's surface against incoming solar UVR. This radiation is damaging to living organisms, and hazardous to human health.

Climate change and stratospheric ozone depletion are themselves part of a wider complex of global environmental changes that are attributable to human activities. These changes reflect an apparent recent overloading of many of Earth's natural systems. They include loss of biodiversity, declines in ocean fisheries, widespread land degradation, disturbances of marine ecosystems and depletion of freshwater supplies (McMichael, 1993). They have two important implications for scientific research.

Firstly, since these various environmental stresses coexist, the impact of any one of them, such as climate change, will be influenced by the particular local combination of stressful exposures of which it forms a part. For example, if climate change were to increase local malaria transmission potential by contributing to increased vector densities, the actual impact on human health might be modified by coexistent malnutrition (perhaps arising from degradation of local cropland) and a greater burden of other infectious diseases (in part due to immune-suppressive effects of increased UVR). Scientific research must therefore seek to develop more integrated systems-based models and analyses of complex environmental processes. This will require a greater commitment to multidisciplinary research.

Secondly, effective policy solutions cannot be piecemeal. Many of the global environmental changes that are now taking place have common origins in the scale and type of contemporary human economic activity that triggered them and so require concerted, coordinated action for their resolution. Population growth, the spread of industrialization and modern transport systems, the expansion of energy-intensive agriculture and livestock production, urban migration, increased consumerism, the rapid evolution of electronic communication networks, and the emergence of a world economy: all these are affecting the global environment in ways we might not have thought possible several decades ago. Accordingly, scientific assessments of society's response options — their relative effectiveness and their (fully-costed) cost–efficiency — must take account of different possible configurations of policy responses.

The large-scale nature of the processes involved in climate change cannot be overemphasized. Until recently, the impacts of human societies upon the environment tended to be much more limited and localized — for example, industrial emissions of chemical pollutants have affected the surrounding air and water; and erosion has degraded local farmland. But changes in the world's lower and middle atmospheres are global in extent; their effects on human health and well-being are therefore likely to impinge widely and over a prolonged time-scale.

Growing awareness of climate change has stimulated recent attempts to assess its likely health impacts. In particular, the UN's Intergovernmental Panel on Climate Change (IPCC) has comprehensively reviewed the scientific literature on this topic (McMichael et al., 1996) (see Box 1.1). This awareness has also focused attention on the relationship between climate and human health. In the past, variations in climate were less interesting to environmental health researchers than environmental pollution and degradation: climate variations were considered to be naturally-occurring and beyond the control of human society. But with the understanding that human activities are largely responsible for anticipated global climate change, a number of new research foci are emerging. These are described below.

Research foci

Research into the relationship between climate and health is currently focusing on:

- the impact upon human health of naturally-occurring short-term fluctuations in climate (including extreme weather events) and of geographically-based differences in background climate;
- the ways in which certain recent regional and local changes in climate patterns may have affected human health already — for example, El Niño/Southern Oscillation-related climate processes have been associated with regional droughts, altered patterns of some vector-borne infections, and disturbances in various marine ecosystems;
- forecasting (by extrapolation, predictive modelling and theoretical reasoning) of the health impacts that are likely to occur because of human-induced climate change.

The first of these three categories is being addressed by conventional, empirical, data-based research. That is, causal relationships are inferred and quantified from observations of variations in climatic exposures and resultant health outcomes in human populations.

By contrast, the third category does not depend upon direct empirical observation. Rather, it entails the forecasting of future health impacts and employs an "if–then" logic. It asks: "*If* the climate changes to Scenario X, *then* what would be the likely health impact?"

Research carried out under the second category is examining selected recent examples of local changes in climate in relation to putative health outcomes, as an analogue for studying the likely health impacts of future climate change. For example, recent increases in the range of some mosquito-borne diseases in Central America probably reflect the combined influences of environmental, climatic and demographic changes. Our increasing interest in these potentially climate-related "signals" is alerting us to how ecosystems may respond to future climate shifts and to how our health might in turn be affected.

All three of these research foci are addressed in this book. Knowledge of the relationship between natural variations in climate and health is important in its own right; climates will continue to fluctuate and there is still much to learn about the health consequences. That knowledge also provides a basis for forecasting the potential health impacts of longer-term climate *change*. However, much of that forecasting will require more knowledge than is provided by this conventional knowledge base. If long-term shifts in background climate patterns lead to changes in species distributions, in the resilience of ecological communities, in sea levels and in freshwater supplies, then unusual types and configurations of health impact should be anticipated. For example, in the absence of prior equivalent experience we cannot foretell exactly how a sustained increase in winter temperature and an accompanying change in seasonal rainfall patterns would influence the range of vector-borne diseases. Similarly, we cannot predict the range and scale of public health consequences that would follow permanent coastal population displacement caused by rising sea levels. However, this information gap can be breached partly by the second category of research, using recent historical experience as an analogue for future climate change.

Understanding of climate change

In 1986, WMO, together with WHO and UNEP, convened a scientific meeting in Leningrad to review the relationship between climate and human health. The meeting focused on the health impacts of present natural variations in climate rather than possible future climate changes (WMO, 1987). Meanwhile, during the mid-1980s, the adverse biological consequences of stratospheric ozone depletion had been discussed at several high-level scientific conferences, prior to adoption by national governments of the Montreal Protocol in 1987.

The potential health impacts of global climate change due to GHG accumulation attracted less attention. Initial scientific concerns about the impacts of climate change focused on damage to natural and managed ecosystems, economic dislocations, disturbances of human physical settlements, and enforced human migration. *Our common future*, the report of the UN World Commission on Environment and Development (WCED) (1987), did not examine the relationship of environment and development to human health in any detail, although concern for the sustained health of human populations was implied.

Subsequently, various developed country national governments began to examine the issue of climate change and human health. In 1989 the US Environmental Protection Agency (USEPA) submitted a report addressing this relationship in detail to US Congress (USEPA, 1989). In Europe, *The European charter* on environment and health paid some attention to this relationship, as did subsequent reports produced by member countries, such as the Netherlands (WHO, 1990a). In Australia, the National Health and Medical Research Council (NHMRC) commissioned a report entitled *Health implications of long term climatic change* (NHMRC, 1991). More recently, the Canadian Global Change Program (CGCP), through its Health Issues Panel, published its assessment of climate change impacts upon health (CGCP, 1995). In 1995, the UK Government commissioned the Climate Change Impacts Review Group (CCIRG) to assess the possible impacts of climate change, including potential health impacts, within the UK (CCIRG, 1996). Various developing countries have also been conducting scientific assessments of climate change, under the sponsorship of the US Country Studies Program. Ultimately, the participating study teams will develop national strategy documents identifying their country's vulnerabilities to climate change and providing recommendations concerning adaptive options (Benioff, Guill & Lee, 1996).

In 1996, the IPCC, a large multidisciplinary body of scientists established within the UN framework in 1988 by WMO and UNEP, published its *Second assessment report*. This report gave substantive attention and considerable prominence to the potential health impacts of climate change (see Box 1.1). This was in marked contrast to its first report which referred only briefly to health impacts, as follows:

> "In coastal lowlands such as in Bangladesh, China and Egypt, as well as in small island nations, inundation due to sea level rise and storm surges could lead to significant movements of people. Major health impacts are possible, especially in large urban areas, owing to changes in the availability of water and food and increased health problems due to heat stress and spreading of infections. Changes in precipitation and temperature could radically alter the patterns of vector-borne and viral diseases by shifting them to higher latitudes, thus putting large populations at risk. As similar events have in the past, these changes could initiate large migrations of people, leading over a number of years to severe disruptions of settlement patterns and social instability in some areas . . . Global warming and increased UV radiation resulting from depletion of stratospheric ozone may produce adverse impacts on air quality such as increases in ground-level ozone in some polluted urban areas" (IPCC, 1990a).

In that same year, WHO (1990b) published a report by an expert panel on the *Potential health effects of climate change*. It paid particular attention to the health impacts that could result from heat stress, enhanced air pollution, malnutrition due to impaired food productivity, an altered pattern of vector-borne diseases (such as malaria and schistosomiasis), and inundation. Subsequently, the report of WHO's Commission on Health and Environment (1992), *Our planet, our health*, gave some attention to climate change in relation to health impacts arising from "transboundary and international problems". But it concentrated primarily on localized environmental health hazards arising from industrial pollution, agricultural practices, urban crowding, and contaminated drinking-water. Meanwhile, UNEP has published assessments of the extent and impacts of stratospheric ozone depletion, forecasting changes in the incidence of skin cancer and cataracts of the eye (UNEP, 1991; 1994a).

The publication of the *IPCC second assessment report* has raised markedly the profile of population health impact as a criterion for policy-making relating to climate change (IPCC, 1996a; 1996b). This applies particularly within the context of the UN Framework Convention on Climate Change, which originated at the UN Conference on Environment and Development (UNEP/WMO, 1992). Article 1 of that Convention defines "adverse effects of climate change" as including significant deleterious effects upon "human health and welfare".

This book presents an updated assessment of the potential health effects of climate change. The substantial overlap of authors involved in the preparation of this book, and of the health impact chapter for the above-mentioned IPCC *Second assessment report*, means that much of the research referred to here also provided the basis of that chapter.

Recent developments in scientific methods and concepts

Assessment of the potential health impacts of climate change is an unusually contingent exercise. It must take account of the assessment by climatologists of when, where and to what extent the ongoing accumulation of GHGs will translate into changes in climate, and also of the assessment by other scientific disciplines of how those climate changes could affect the world's biogeophysical systems. A basic understanding, at least, of the nature and limitations of those "upstream" assessments is therefore important.

The climate prediction models used during the 1990s have been progressively refined. They now incorporate an enhanced capacity to couple atmospheric and oceanic processes, to take account of the cooling effect of industrial aerosols in the atmosphere (predominantly very fine sulfate particles from fossil fuel combustion, which reflect away some of the incoming solar energy), and to deal with cumulative changes in atmosphere and climate. They can also make more detailed regional predictions of climate change than formerly. These advances reflect both an improved understanding of the interaction between natural systems, and a greater facility for linking modular, system-specific, models. Nevertheless, because of the complexity of the climate system and the possibility of non-linear responses as atmospheric composition and processes move beyond normal bounds, uncertainties persist in the predictive modelling of future climate scenarios.

Most of the health impacts of climate change would be mediated by changes in other systems or processes — such as the distribution of vector organisms, levels of food production, proliferation of bacteria, and availability of water supplies. Predictions of the health impacts of climate change are therefore likely to contain many uncertainties and these must also be considered. (Relevant details are discussed in later chapters.)

Meanwhile, in the health sciences arena, the techniques of environmental health risk assessment as applied to local environmental exposures are developing further. This requires two sets of information: the best estimate, from the published literature, of the dose–response relationship between the "exposure" factor and the health outcome; and an estimation (or prediction) of the current (or future) exposure profile of the population under consideration. From these two sets of information, the aggregate impact of the particular exposure upon the health of the population can be estimated.

However, for most of the potential health impacts of climate change, empirical information upon which to base a standard risk assessment remains inadequate. For a minority of the anticipated impacts, such as mortality due to heat waves or skin cancer incidence due to increased UV exposure, an extension of standard risk assessment methods is possible. But for other health impacts, either new modelling techniques are required, or else it is not yet appropriate to attempt to quantify impacts. The particular challenges to the discipline of epidemiology — the body of scientific ideas and methods used to describe the patterns of health and disease in populations and to determine the causation of those diseases — are discussed in the following section.

Box 1.1. Executive summary from IPCC *Second assessment report 1995*

The sustained health of human populations requires the continued integrity of Earth's natural systems. The disturbance, by climate change, of physical systems (e.g. weather patterns, sea level, water supplies) and of ecosystems (e.g. agroecosystems, disease-vector habitats) would therefore pose risks to human health. The scale of the anticipated health impacts is that of whole communities or populations (i.e. it is a public health, not a personal health, issue). These health impacts would occur in various ways, via pathways of varying directness and complexity, including disturbance of natural and managed ecosystems. With some exceptions, relatively little research has yet been done that enables quantitative description of these probable health impacts.

It is anticipated that most of the impacts would be adverse. Some would occur via relatively direct pathways (e.g. deaths from heat waves and from extreme weather events); others would occur via indirect pathways (e.g. changes in the range of vector-borne diseases). Some impacts would be deferred in time and would occur on a larger scale than most other environmental health impacts with which we are familiar. If long-term climate change ensues, indirect impacts would probably predominate.

Populations with different levels of natural, technical and social resources would differ in their vulnerability to climate-induced health impacts. Such vulnerability, due to crowding, food insecurity, local environmental degradation and perturbed ecosystems, already exists in many communities in developing countries. Hence, because of both the geography of climate change and these variations in population vulnerability, climate change would impinge differently on different populations.

- An increased frequency or severity of heat waves would cause an increase in (predominantly cardio-respiratory) mortality and illness. Studies in selected urban populations in North America, North Africa and East Asia indicate that the number of heat-related deaths would increase several-fold in response to two GCM-modelled climate change scenarios for 2050. For very large cities, this would represent several thousand extra deaths annually. Although this heat-related increase in deaths would be partially offset by fewer cold-related deaths, data to quantify this tradeoff are insufficient; further, this balance would vary by location and according to adaptive responses.
- If extreme weather events (droughts, floods, storms, etc.) were to occur more often, increases in rates of death, injury, infectious disease and psychological disorder would result.
- Net climate change-related increases in the geographic distribution (altitude and latitude) of the vector organisms of infectious diseases (e.g. malarial mosquitos, schistosome-spreading snails) and changes in the life-cycle dynamics of both vector and infective parasites would, in aggregate, increase the potential transmission of many vector-borne diseases. Malaria, of which currently around 350 million new cases occur per year (including two million deaths), provides a central example. Simulations with first-generation mathematical models (based on standard climate-change scenarios and

incorporating information about the basic dynamics of climatic influences on malaria transmission) predict an increase in malaria incidence in Indonesia by 2070 and — with a highly-aggregated model — an increase from around 45% to around 60% in the proportion of the world population living within the *potential* malaria transmission zone by the latter half of the next century. Although this predicted increase in *potential* transmission encroaches mostly into temperate regions, actual climate-related increases in malaria incidence (estimated by one model to be of the order of 50–80 million additional cases annually, relative to an assumed global background total of 500 million by 2100) would occur primarily in tropical, subtropical, and less well protected temperate-zone populations currently at the margins of endemically infected areas. Some localized decreases may also occur.

- Increases in non-vector-borne infectious diseases such as cholera, salmonellosis, and other food- and water-related infections could also occur, particularly in tropical and subtropical regions, because of climatic impacts on water distribution, temperature and microorganism proliferation.
- The effects of climate change upon agricultural, animal, and fisheries productivity, while still uncertain, could increase the prevalence of malnutrition and hunger and their long-term health impairments, especially in children. This would most probably occur regionally, with some regions likely to experience gains, and others losses, in food production.
- Many health impacts could also result from the physical, social, and demographic disruptions caused by rising sea levels and by climate-related shortages in natural resources (especially fresh water).
- Because fossil fuel combustion produces both carbon dioxide and various primary air pollutants, the climate change process would be associated with increased levels of urban air pollution. Not only is air pollution itself an important health hazard, but hotter temperatures, in urban environments, would enhance both the formation of secondary pollutants (e.g. ozone) and the health impact of certain air pollutants. There would also be increases in the frequency of allergic disorders and of cardiorespiratory disorders and deaths caused by various air pollutants (e.g. ozone and particulates).
- A potentially important category of health impact would result from the deterioration in social and economic circumstances which might arise from adverse impacts of climate change on patterns of employment, wealth distribution, and population mobility and settlement. Conflicts might arise over dwindling environmental resources.
- Stratospheric ozone is being depleted concurrently with greenhouse gas accumulation in the troposphere. Although there are some shared and interactive atmospheric processes between disturbances of the stratosphere and troposphere, both they and their health impacts arise via quite distinct pathways. A sustained 10–15% depletion of stratospheric ozone over several decades would cause increased exposure to ultraviolet radiation and an estimated 15–20% increase in the incidence of skin cancer in fair-skinned populations. Lesions of the eye (e.g. cataracts) may also increase in frequency, as might vulnerability to some infectious diseases via adverse effects on immune function.

Source: Chapter 18: Human population health, McMichael et al., 1996 (abridged).

It is also important to note that the health impacts of climate change will almost certainly vary greatly between geographic regions and different populations for a mix of climatic, environmental, biological, cultural and socioeconomic reasons. In particular, populations already disadvantaged by poverty, urban crowding, malnutrition, and general lack of technical and social resources, are likely to be more vulnerable to the impacts of climate change than non-disadvantaged populations.

Assessing the significance of climate change impacts upon health also requires a sense of perspective. For example, recent model-based predictions (see Chapter 4) of an increase next century in the annual global incidence of malaria of 50–80 million, due to climate change, would be relative to a likely background incidence of 400–500 million. Taking account of other potential changes that could alter foreseeable trends — in this instance, the possible future discovery of an effective vaccine for malaria — introduces further difficulty.

The impacts of climate change upon health must be assessed against a constantly changing background. Put very succinctly, population health status, influenced by a diversity of factors, varies over time. Infectious diseases rise and fall in response to the rhythms and disjunctions of nature and in response to local demographic, cultural and technological changes. Food supplies are affected by natural disasters, the abundance of pests and predators, civil war, and patterns of commerce. Chronic non-infectious diseases, such as heart disease, diabetes and cancer, reflect much about levels of material development and their associated lifestyles. Each of these elements of population health must be considered when assessing the health impacts of climate change. However, it is not possible to give details of the state of the world's health — beyond those included in Box 1.2 — here. This information is available, though, from a variety of sources, and has been summarized comprehensively by WHO (1995a; 1996).

For all of the reasons discussed above, few quantitative forecasts of the health impacts of climate change have been made in this book. This is not a serious limitation at this stage of enquiry, since the primary need is to assess the range and likelihood of these impacts. As has already been stressed, this is an "if . . then" question. *If* the world's climate changes, *then* what would be the impacts upon the health of human populations? Likewise, this book does not attempt a detailed assessment of the climate change process *per se*. Rather, it first summarizes the state of knowledge and the prevailing expert views about human-induced climate change, and then takes these as the basis for assessing potential health impacts and, subsequently, for discussing policy response options.

The challenge to environmental epidemiology

Epidemiology is a relatively young science (Rothman, 1986). It has developed over the past two centuries, primarily in response to the combined stimuli of the pattern and burden of infectious and non-infectious diseases in urbanizing developed countries, recognition of the need for public health strategies, and the parallel development of biomedical sciences, especially toxicology, immunology and molecular biology. The recent evolution of the basic principles of the design and conduct of epidemiological studies has occurred largely as a result of the rise of chronic degenerative diseases of later adulthood (an historical novelty). Often, new epidemiological concepts and methods, along with new interdisciplinary liaisons, have emerged from exploring the causal processes underlying common disease problems and their apparent associations: for example, cholera and water supply, mosquitos and malaria, and smoking and lung cancer. But as

Box 1.2. Current trends in world health

Information about current levels of and time-trends for specific health outcomes provides a frame of reference for appraising the projected health impacts of climate change. Where possible, those impacts should be differentiated from projected changes in health outcomes due to other independent factors.

The main contemporary features of world health include:

- near-worldwide increases in life expectancy, with the general exception of the ex-Eastern Bloc countries;
- a decline in infant and child mortality in most developing countries;
- persistent gaps in health status between rich and poor (within and between populations);
- reductions in incidence of certain vaccine-preventable diseases (e.g. polio and measles);
- increased incidence of chronic non-infectious diseases of adult life (especially heart disease, diabetes and certain cancers) among urban middle-classes in rapidly developing countries;
- widespread increases in the incidence of HIV/AIDS.

The tempo of new (emerging) and resurging infectious diseases appears to have increased. This may reflect combined environmental and demographic changes in the world, along with increases in antibiotic, drug and pesticide resistance. For example, the interaction of local climate change with ecosystem disruption may have facilitated the emergence of rodent-borne hantavirus pulmonary syndrome in the USA during 1992–1993. Similar configurations of environmental stress may have contributed to the emergence of various rodent-borne arenaviruses in Africa and South America, the spread of toxin-producing algal blooms, and the occurrence of dengue in new geographic areas and the occurrence of malaria at higher latitudes than recorded previously. Given this dynamic backdrop of infectious disease incidence, and further increases in environmental stresses, population density and the long-distance mobility of persons and organisms, global climate change is likely to become an important influence upon future patterns of infectious diseases.

Many other important influences on population health are changing and will interact with the effects of climate change. For example, new vaccines are being developed, and existing ones are becoming more widely used; contraception is gradually becoming more widespread, with benefits to maternal and child health; and safe drinking-water is becoming available to an increasing number of householders in poorer countries. Conversely, adverse health effects arising from tobacco use, drug abuse, urban traffic pollution, social breakdown and violence are also increasing widely, notably within large cities. In particular, with the tobacco industry taking advantage of freer trade and market-based economies, rates of disease and death from cigarette smoking are expected to escalate markedly among women worldwide and in both sexes in most non-industrialized countries.

Sources: Morse, 1991; Herrera-Basto et al., 1992; World Bank, 1993; CDC, 1994a; Feachem, 1994; Levins et al., 1994; Morse, 1995; WHO, 1995a; 1996.

a primarily observational (i.e. non-experimental) science, epidemiology faces the difficulties posed by gathering data in intrinsically "noisy" field settings (where many factors co-vary), and by measurements of exposure and disease that are seldom made under fully controlled conditions. Additionally, it requires the cooperation of many people, and studies typically take considerable time and effort.

Environmental epidemiology focuses on elucidating and quantifying the relationship between exposure to environmental factors, such as radiation and chemical pollutants, and occurrence of disease. It draws upon empirical evidence from field studies of human populations and experimental evidence from human-volunteer and toxicological studies. One of its most important activities is the estimation of dose–response relationships. These are crucial for standard setting, to maintain environmental quality. For example, projected emission levels are typically applied to previously established dose–response relationships to assess the potential impacts of impending industrial or engineering projects. In other words, predictions are made of future health impacts that might occur *if* the projected environmental stresses were to occur. Such assessment has become a common legislative component of environmental impact assessment in many countries. If the predicted health impacts are likely to exceed a preset "acceptable" standard, mitigation measures may be stipulated or the project even banned. Alternatively, although uncertainties may remain about health impacts, the associated risks may be judged minimal and remediable. In which case, the go-ahead may be given, on condition that a monitoring system is established.

Prediction of the human health impacts that might result from global environmental change involves considerably greater uncertainty. And environmental epidemiology has few appropriate research tools with which to meet this immense challenge, consisting as it does of a novel combination of global scale, long timeframes, complex processes, and all of the uncertainties attached to scenario-based forecasting (including the uncertainties inherent to climate-change modelling and its currently limited spatial resolution). Similarly, the process of primary prevention (reduction of GHG emissions) will be very uncertain because it is governed by technological, political and economic forces. Moreover, the large time-lags involved in climate change may mean that any unforeseen negative consequences will prove very difficult to correct (see also Chapter 9).

Potentially, the population at risk from climate change includes the whole human population. Modern epidemiological methods, however, focus upon explaining differences in health risk between categories of individuals within a single population. They are therefore ill-equipped for assessment of the future population-level health impacts of climate change. The microbiological environment of such populations might undergo major changes in species composition, human immune systems may be weakened by climatically-induced food shortages and increased UV-B exposures, and local economies may be affected by climatic change and weather extremes. The range of potential health impacts is thus very wide — although those due to physical disaster, increased infectious diseases and malnutrition are easier to assess than those linked to the social and demographic consequences of disruption, displacement and impoverishment of communities.

That said, challenges to epidemiological science have historically led to innovation. Indeed, environmental epidemiology is already responding to the perceived health hazard of global climate change. In the past two years, natural climate variation, in particular the El Niño/Southern Oscillation, and associated variations in health impacts, have received increasing attention from epidemiologists seeking analogues for climate change. As a result, first-generation mathematical models have been developed for forecasting global changes in the distribution of vectors and pathogens of tropical diseases in response to climate change. Data collected from improved disease monitoring systems and from increasingly sophisticated climatological and oceanographic monitoring, will enable construction of more "true-to-life" predictive models.

This major new effort in public health science requires more intensive cooperation between environmental epidemiology and the biological and social sciences. More generally, the understanding and amelioration of complex, global problems calls for some fundamental shifts in scientific concepts and methods, and in the handling of unavoidable uncertainty by scientists and society at large.

Climate change and human health: the nature of the relationship

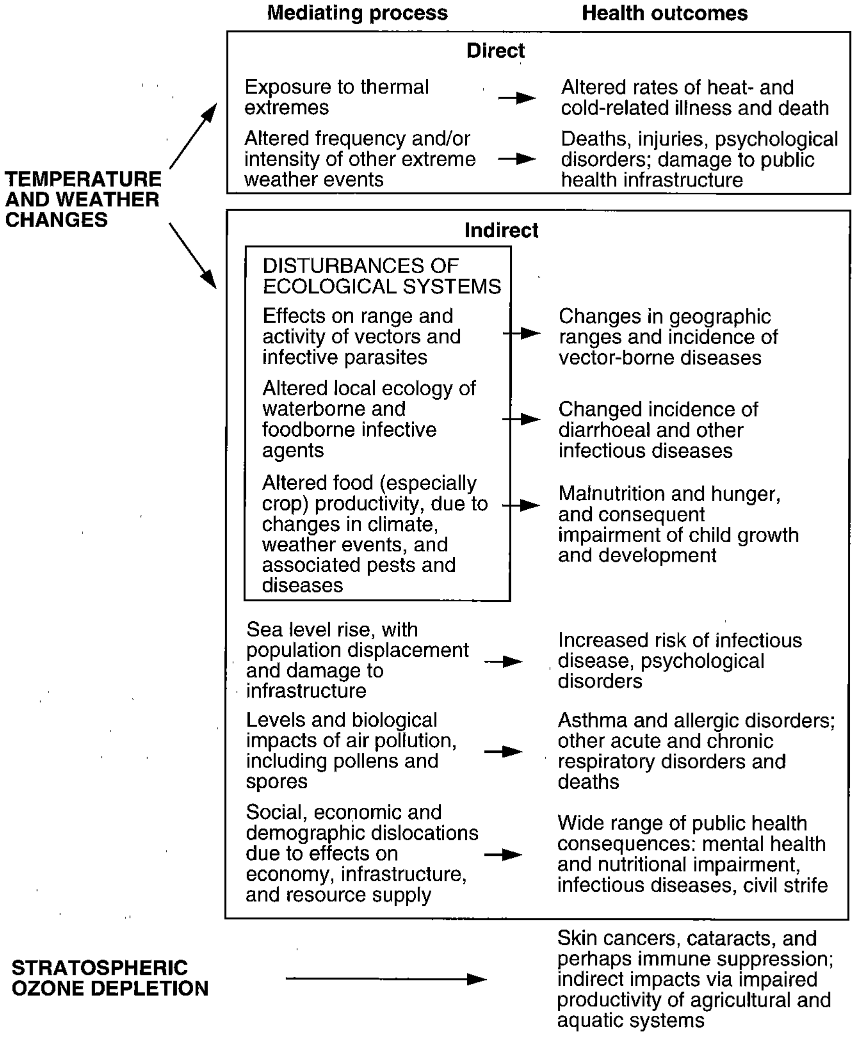
Basing their projections on the most likely future trends in economic activity (and therefore in gaseous emissions), climate scientists participating in the work of the IPCC predict that the mean surface temperature of Earth will increase by around 1–3.5°C over the coming century (IPCC, 1996a). This would be an unprecedentedly rapid rate of change for the world's human population. This temperature increase would vary by latitude and region, and would be associated with changes in precipitation patterns and possibly with changes in climate variability. Since higher temperatures would cause oceans to expand and glaciers to melt, mean global sea level is forecast to rise by around one-third to one-half a metre by 2100.

In the meantime, stratospheric ozone depletion will continue, and is anticipated to do so for at least another decade. By 1995, the annual average loss of ozone at mid-latitudes was approximately 10% (Bojkov, 1995). Since ozone depletion is caused by gases that also contribute to heat entrapment in the troposphere, and since ozone depletion affects atmospheric heat transfer and distribution at higher altitudes, including the topic within this book was deemed appropriate. However, there is an important basic distinction between the causes and consequences of these disturbances to the lower and middle atmospheres. Hence, unless otherwise specified, the phrase "climate change" will be used here to refer to the former change, caused by GHG accumulation.

Climate and the many natural processes influenced by climate are a fundamental component of Earth's life-supporting mechanisms. To a biologist, therefore, it is axiomatic that a change in climate would influence the prospects for health and survival of each and every species in the ecosystems affected. Accordingly, it is reasonable to anticipate that the health of *Homo sapiens* — notwithstanding its unique capacity to develop and transmit culture and thereby to control environments — would be affected by global climate change. And in view of the rapid *rate* of projected climate change over the coming century, many of these health impacts can be expected to be serious.

It is important to emphasize again that the environmental hazard framework being considered here is much broader and more complex than that which typically applies to assessing environmental health risks to human populations. The contamination of local environments with noxious industrial, agricultural and automotive wastes poses a direct and tangible toxic threat to human biology. In contrast, the emission of GHGs has no direct toxic consequence for humans but may alter various environmental conditions and ecological relationships that may then influence human health.

Fig. 1.1. Possible major types of impact of climate change and stratospheric ozone depletion on human health



The range of possible major types of health impact is shown in Fig. 1.1 (and in Box 1.1). For ease of presentation, the impacts have been classified as direct or indirect, according to whether they occur predominantly via the impact of a climate variable (such as temperature or extreme weather events) upon human biology, or are mediated by climate-induced changes in other biological and geochemical systems.

Some relatively simple direct (and therefore more readily predictable) impacts of, for example, heat waves, storms or rising seas could be anticipated. Via less direct pathways, changes in background climate may, for example, alter the distribution and behaviour of mosquitos and the life cycle of the malarial parasite, so that malaria patterns change. Many other vector-borne diseases could be affected in a similar way. Climate change would also affect agricultural productivity, and could therefore influence nutritional status, hunger and health. More generally, the physical

Table 1.1. Likely relative impact on health outcomes of the components of climate change

Health outcome	Aspects of climate change: change in mean temperature, etc.	extreme events	rate of change of climate variable	day–night difference
Heat-related deaths and illness		+++		+
Physical and psychological trauma due to disasters		++++		
Vector-borne diseases	+++	++	+	++
Non-vector-borne infectious diseases	+	+		
Food availability and hunger	++	+	++	
Consequences of sea level rise	++	++	+	
Respiratory effects:				
- air pollutants	+	++		+
- pollens, humidity	++			
Population displacement	++	+	+	

++++ = great effect; + = small effect; empty cells indicate no known relationship.

damage, habitat loss and species depletion suffered by the marine and terrestrial ecosystems — such as pastoral lands, ocean fisheries, and wetlands — that maintain environmental services essential to sustained human health, may be exacerbated by climate change. The different aspects of climate change would of course vary in their relative importance for different health impacts. This is illustrated in Table 1.1. However, our knowledge in this area is incomplete.

The population-level dimension of the climate–health relationship must be emphasized. The scale of predicted climate change and its health impacts applies to whole populations or communities, rather than to small groups or individuals. Hence, assessment of the health impact of climate change must focus on changes in the rates of death, disease or other health impairments in whole regions, populations and communities. This is not an environmental hazard for which risks can be differentiated and estimated at the individual or small group level.

Contents and objectives of this book

The need to extend the discussion of climate change to include consideration of the impact on human health is newly-recognized. Much of the discussion of climate change to date has concerned its more immediate socioeconomic and environmental consequences. A premise underlying this volume is that we must now think carefully, and within an ecological framework, about the longer-term implications for human health of disturbing or damaging components of the biosphere.

Accordingly, this book explores the context and processes of GHG accumulation and stratospheric ozone depletion, and the changes in world climate patterns and UVR exposure that could result. It reviews current knowledge about how natural climate fluctuations affect health and examines in detail the various likely health impacts of human-induced climate change. It also discusses the challenges that this topic presents to orthodox science, the need to investigate it using ecologically-based approaches, and the need for coordinated multi-level monitoring of health-related indices.

In a little more detail:

In Chapter 2, the processes of climate change are reviewed, as are the computer models used for predicting those changes. The major components of potential climate change are identified as follows: changes in temperature, precipitation, and extreme weather events; and changes in sea level. The causes of and trends in stratospheric ozone depletion are also examined.

In Chapters 3–7, the potential impacts on human health of the major components and/or consequences of climate change are assessed for: thermal stress and exacerbation of air pollution hazards; infectious diseases; food production; extreme weather events; sea level rise. Chapter 8 examines the potential impacts on human health of stratospheric ozone depletion. A spectrum of health impacts is discussed for each component or consequence of climate change, ranging from the more predictable direct effects (for example, increased mortality due to greater frequency of heat waves or cyclones, and increased incidence of skin cancers due to increased UVR levels), to the less certain and more complex indirect effects (for example, increased incidence of malnutrition due to impaired crop productivity, and population displacement due to sea level rise). In reality, of course, much interaction would occur between coexistent climate-related environmental stresses in the production of health impacts.

In Chapter 9, the methods of studying the relationship between climate and human health are described, as are the approaches used by the major contributory disciplines. The ecological dimension of the climate–health relationship is explored, including the fact that its inherent unfamiliarity means that there is little empirical experience or information upon which to base predictions of health impacts. The chapter also notes the role of the social sciences, especially economics (appropriately adapted), in assessing and managing these problems. Finally, it examines the close link between research and coordinated monitoring of health-related indices, stressing the need for the latter to serve both as an information source for society and policy-makers, and as a source of continuous feedback for the research and impact assessment process.

The final chapter considers broad strategies for the prevention (or mitigation) of climate change and for the amelioration of its health impacts. Conclusions are drawn, and recommendations made for research priorities and for preventive policies — in accordance with the Precautionary Principle. This principle bids us to not take unnecessary risks with the future, especially if their avoidance entails no material detriment or inequity in the short term.

Indeed, from the research perspective, if adverse population health impacts are likely to result from climate change, we do not have the usual option of seeking definitive empirical evidence before acting. With local environmental health hazards such as air pollution or pesticide exposures, we first conduct local studies which, if positive, then legitimize our taking preventive action on behalf of other potentially exposed populations. However, when the environmental health hazards arise from ecologically disruptive and potentially irreversible global environmental processes, such a wait-and-see approach would be imprudent at best and nonsensical at worst.

Key terms

Several of the basic terms and phrases used in this book need to be defined. Firstly, various words are used to refer to the anticipation of future events and their impacts. Whereas one makes an *estimate* of some already-existing value from a sample of data collected in the real world, a *prediction* refers to a future eventuality. However, the word "prediction" can sound more certain, more precise, than it really is. Hence, many of the scientists studying climate change, sensitive to the inherent uncertainties and the assumptions underlying the selected scenarios, prefer to talk about *projections* or *forecasts*. All these words are used in this book, and this often reflects nuances of context or the particular scientific literature that is being cited.

Secondly, the phrase "ecologically sustainable" is used in relation to society's development trajectory and to human health. The word "sustainable" has recently been used, and misused, in many contexts. At its simplest, sustainability refers to the ability to continue to undertake an activity indefinitely. In *Our common future* (WCED, 1987) sustainability is used to refer to the obligation to meet the needs of the existing generation without compromising the needs of future generations. This might seem to refer principally to an equitable rationing, over time, of the use of non-renewable resources (fossil fuels, strategic metals, natural building materials, and so on). In this book, however, we are more explicit about the nature and needs of renewable resources and ecosystems that may otherwise be damaged beyond a point of reversibility. Sustainability is thus taken to refer to ensuring that the biosphere and its component ecosystems remain intact and productive, so that life on Earth is able to continue drawing sustenance from them.