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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

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

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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.

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Director-General	Secretary-General	Executive Director
World Health Organization	World Meteorological Organization	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.

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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 x 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

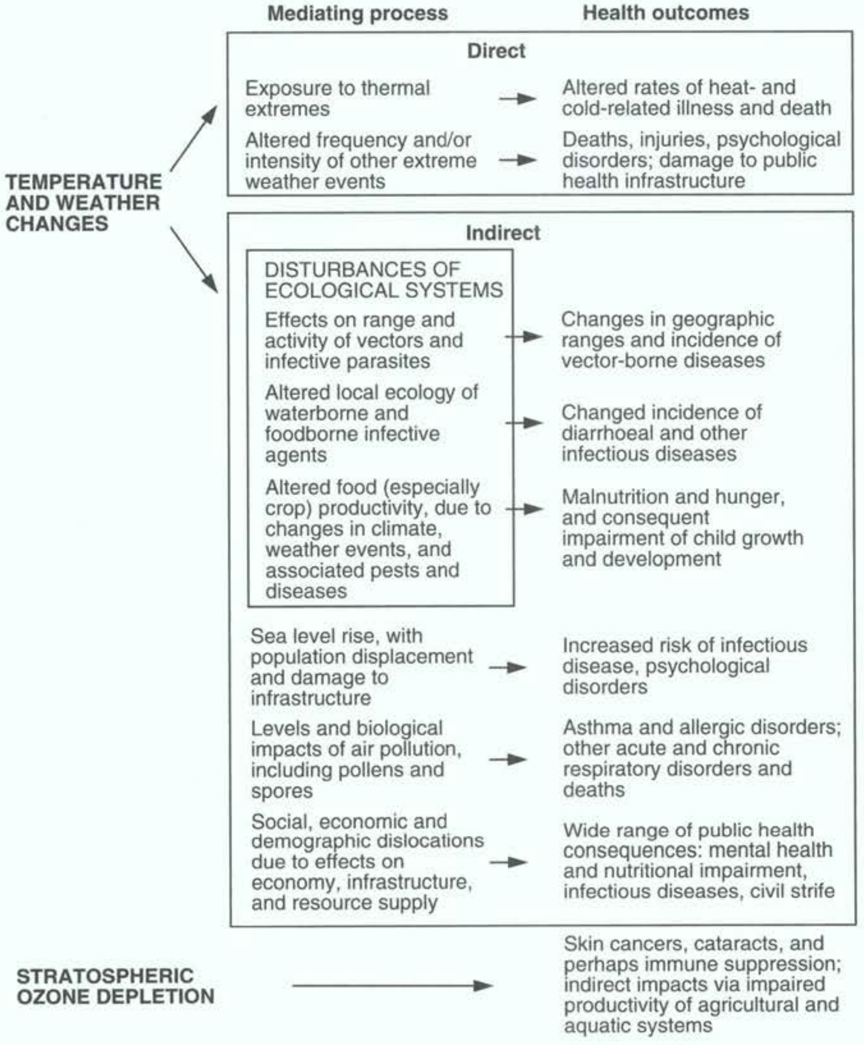
Basing their projections on the most likely future trends in economic activity (and therefore in gaseous emissions), climate scientists participating in the work of the IPCC predict that the mean surface temperature of Earth will increase by around 1–3.5°C over the coming century (IPCC, 1996a). This 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.

Chapter 2

The climate system

Human activity and global climate change

Because of the heat-trapping properties of the so-called greenhouse gases (GHGs), the average surface air temperature is approximately 15°C, which is about 33°C higher than it would otherwise be. In other words, in the absence of this "greenhouse effect" most of Earth's surface would be frozen, at a mean air temperature of -18°C.

Ever since the beginning of the Industrial Revolution (c.1750–1800), the emission of GHGs has been rising dramatically due to increased industrial and agricultural production, and increased use of fossil fuel for domestic heating. The atmospheric concentration of carbon dioxide (CO_2), for instance, the main GHG, has increased by 30% since pre-industrial times (IPCC, 1994a). At about 358 ppmv, atmospheric CO_2 concentration is now higher than at any other time since the modern human species (*Homo sapiens*) first came into existence 160 000 years ago.

The main effect of increased emission of GHGs has been enhancement of this heat-trapping capacity, a process known as radiative forcing. This is resulting in an enhanced greenhouse effect, or global warming (see Box 2.1). GHG emissions have therefore become a matter of global rather than just local concern, particularly since, given their long atmospheric lifetimes, GHGs are now evenly dispersed throughout the atmosphere (Watson et al., 1992).

In 1988, concern over anticipated global climate change and its consequences led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) by WMO and UNEP. Within the IPCC, scientists from various disciplines are organized into three working groups. These groups address the scientific evidence on climate change (Working Group I); the environmental, socioeconomic and health impacts of climate change (Working Group II), and the formulation of response strategies (Working Group III). This chapter reviews the main body of knowledge relating to the scientific understanding of past and present climate as well as of climate variability and potential future change; in other words it covers the province of IPCC Working Group I. It should be noted that the IPCC generally refers to "climate change" as any change in climate, be it natural or induced by human activities. But within the United Nations Framework Convention on Climate Change (UNFCCC), the term is used to refer exclusively to change brought about by human activities.

Brief history of global climate

During the Cretaceous period, 140–65 million years ago, global climate was 10–15°C warmer than it is today, and the atmospheric CO_2 concentration 4 to 8 times higher. However, during the last ice age — from approximately 90 000 to 12 000 years ago — Earth's mean temperature was only 5°C lower than it is today (Graedel & Crutzen, 1994). Thus the transition in Earth's climate which occurred between the last ice (glacial) age and the present interglacial period, occurred gradually, albeit unevenly, over several thousand years (Jaworowski, Segalstad & Ono, 1992). During the current interglacial period, which includes the past 10 000 years, Earth's mean surface temperature has remained fairly constant, with the level of atmospheric CO_2 concentration fluctuating by about ±10 ppmv, at around 280 ppmv, until it started to rise about two centuries ago. The temperature difference between the moderately warm climate of 4–6000 years ago and the Little Ice Age, which occurred between 1400 AD and 1800 AD, was approximately 1°C. On a grand scale, variations in solar radiation and in Earth's orientation and orbit around the sun are thought to be responsible for initiating and ending ice ages.

Defining climate

Climate is defined most simply as the average meteorological conditions experienced in a particular locale, over a specified time period, such as thirty years. Detailed meteorological descriptions include statistics on the mean values and variance of temperature, precipitation, atmospheric pressure, winds, solar radiation and cloud formation. They also include information on the frequency and characteristics of extreme weather events, as well as of seasonal variations. Given the variability and unpredictability of local weather patterns, the need for highly accurate meteorological data and information in order to analyse climate is obvious.

Climate can be classified in terms of its fundamental driving forces. The general circulation of the atmosphere is one of these forces and the basis of a classification system that comprises trade-wind climates, monsoon climates, subtropical climates, maritime versus continental climates, and polar climates. Climate can also be classified according to its spatial scale: for example, macroclimate, mesoclimate and microclimate are terms used for climates of areas of progressively smaller size. Climate impact research and prediction must take scale into account. Higher spatial resolution leads to greater variability but less accurate predictions.

Macroclimate describes the relatively uniform and homogeneous climate of large areas of the globe. It is based mainly on general circulation of the atmosphere, geographical latitude (solar climate), distance from the ocean (maritime vs. continental climate), and elevation above sea level. Temperature changes occur much more quickly on land than in the oceans. Thus the diurnal temperature range — that is, the difference between maximum and minimum temperatures over a 24-hour period — of mid-continent regions may be 20°C. In subtropical desert areas it can reach 30°C. But in coastal areas and on small islands the diurnal temperature range may consist of a few degrees only. Differences between the mean seasonal temperature ranges of different areas or regions are even more marked. For example, this range may be as much as 65°C in north-east Siberia, but as little as 2 or 3°C in equatorial regions.

Mesoclimate refers to atmospheric conditions at intermediate scales of space and time. Tropical cyclones, monsoon circulation and other regional weather systems, which are normally described for a specific geographical situation with its own topography and characteristics such as vegetation cover, belong to the meso-scale. Microclimate refers to local climatic circumstances. A description of a microclimate will incorporate information about the physical processes (such as local wind patterns) of the atmospheric boundary layer, which is the lowest 100–2000 m of the troposphere that is directly influenced by Earth's surface. Urban climates, as well as specific local climates that are determined largely by local land use, belong to this category[1].

[1] Ecologists, however, use the term "microclimate" somewhat differently, to describe the exact atmospheric conditions prevailing in the space surrounding an individual plant or animal.

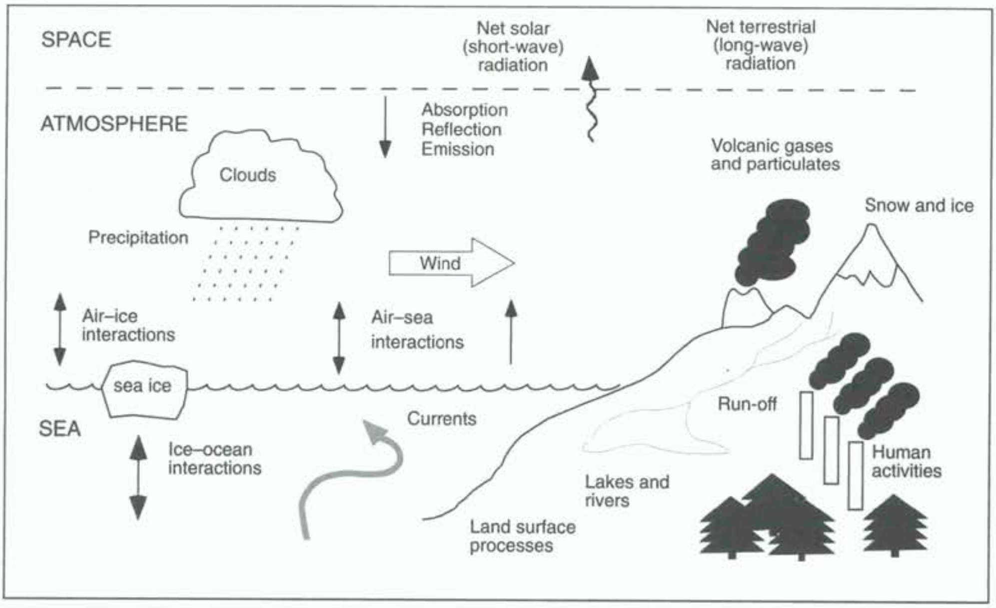
The climate system

The observed climate is the result of complex interactions between the different subsystems shown in Fig. 2.1. The oceans, the land surface, and the ice-coverage of land and oceans, together form the climate system. Atmospheric processes are strongly affected by or "coupled to" these entities. As for the atmosphere, many of its properties are influenced by its gaseous composition, which itself is influenced by animal and plant life on Earth. For example, human activities directly affect the atmospheric concentration of gases such as nitrogen and oxygen, and of trace gases, such as water vapour, CO_2, methane (CH_4) and nitrous oxide (N_2O). Although trace gases account for only 0.3% of atmospheric mass, they play a major role in relation to both the natural and the human-induced greenhouse effect.

Shifts in global climate occur as a result of external factors, such as changes in the balance at the outer edge of Earth's atmosphere between incoming short-wave solar radiation and outgoing terrestrial long-wave (infrared) radiation. A change in this balance can contribute significantly to the net radiative forcing of the atmosphere (see Box 2.1). Positive radiative forcing, which is the process associated with the greenhouse effect, tends to warm Earth's surface, whereas negative radiative forcing tends to cool Earth's surface.

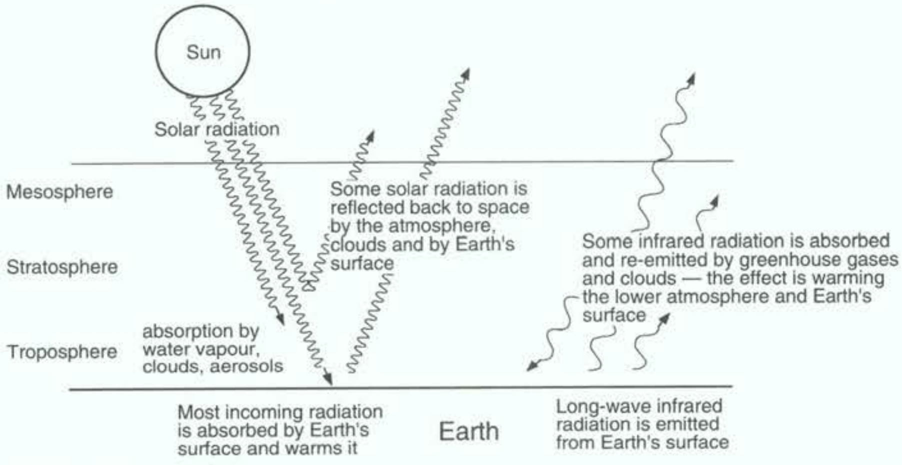
Factors that reduce outgoing long-wave radiation, thereby causing positive radiative forcing, include increases in atmospheric CO_2. Factors that reduce incoming solar radiation and result in negative radiative forcing, include volcanic eruptions, such as those of Mt. Pinatubo in the Philippines, which emit considerable amounts of particles and gases into the upper atmosphere. Negative radiative forcing is also caused by human activities, following the release of industrial aerosols, for example. Indeed, by diminishing solar radiation at ground level, the negative radiative forcing of industrial aerosols may have offset to a considerable extent the climate warming that would have otherwise occurred in recent decades in the northern hemisphere (see Box 2.1).

Fig. 2.1. The climate system



Box 2.1. The greenhouse effect

Of all short-wave solar radiation entering the atmosphere, about one-third is reflected back to space by the atmosphere, clouds and Earth's surface. A smaller fraction is absorbed by water vapour, clouds and aerosols. But most incoming radiation is absorbed by Earth's surface and warms it. The absorbed energy is reradiated as long-wave radiation and redistributed by the atmosphere. Some of the infrared fraction of this terrestrial radiation is absorbed by GHGs: namely, carbon dioxide, water vapour, ozone, nitrous oxide, methane and halocarbons. This energy is again reradiated, but now in all directions, i.e. downwards as well as upwards, so that eventually all radiation is returned to space via the higher, colder levels in the atmosphere. As, according to the laws of thermodynamics, no energy can ever become lost, the total energy emitted back into space equals the total non-reflected incoming solar radiation. However, increased atmospheric concentrations of greenhouse gases slow this emission back into space, which leads to a build-up of heat and alteration in the rate of heat accumulation. This effect increases radiative forcing of Earth's climate.



Source: IPCC, 1994a.

The climate system incorporates many feedbacks, and these account for much of the system's behaviour. A positive feedback amplifies the original "signal" — warming in this instance — whereas a negative feedback diminishes it. An increase in water vapour in the atmosphere due to increased evaporation because of higher temperatures would be an example of a positive feedback. (Water vapour is an important GHG; any increase in water vapour concentration would therefore cause further warming.) The melting of snow and sea ice also constitute a positive feedback since the loss of albedo enhances further warming. Clouds can cause positive or negative feedback with respect to warming, depending on cloud type. Positive feedback leading to warming results from formation of clouds at high altitudes, whereas negative feedback leading to cooling results from formation of clouds at low altitudes.

Within the climate system, the atmosphere is said to be "coupled" to the biosphere and the ocean. Thus the biosphere over land, in the form of forests, for example, is described as a carbon "sink" because it removes CO_2 from the atmosphere for photosynthesis. Forest growth increases in response to increased atmospheric CO_2, removing more CO_2 from the atmosphere in the process, and ultimately reducing the greenhouse effect. As such it is an important negative feedback. The ocean also acts as a sink, but for heat, which is sequestered in its deepest layers. This slows the rise of air temperatures before equilibrium is reached. The time-scales of these various interactions range from several days to many millions of years.

Box 2.2. El Niño/Southern Oscillation

The term "El Niño" was originally used, in a local context, to describe an anomaly in the flow of ocean waters along the west coast of South America, whereby nutrient-rich cold water of the coastal Humboldt Current is replaced sporadically by eastward-flowing warm ocean water from the equatorial Pacific. Since this water lacks nutrients, El Niño events are associated with catastrophic declines in fisheries along the Pacific coast of South America. The effects of El Niño are usually short-lived but sometimes last more than a year, raising sea surface temperatures along the coast of Peru and in the Equatorial eastern Pacific Ocean.

The Southern Oscillation (SO) is a large-scale atmospheric "see-saw" centred over the equatorial Pacific Ocean. More specifically, it is the result of fluctuations in the distribution of high air pressure over the Indian Ocean and the South Pacific. Its period is variable, but averages 2.3 years. The variation in pressure is accompanied in surrounding areas by fluctuations in wind strengths, ocean currents, sea surface temperatures and precipitation.

The Southern Oscillation and the warm waters of the El Niño are part of the same climate phenomenon referred to as ENSO (El Niño/Southern Oscillation). ENSO events are typified by the build-up of high atmospheric pressures over the south-east Pacific and low pressure over Indonesia, over irregular intervals. These in turn result in oscillating fluctuations in wind and ocean currents, leading to changes in mean regional temperature and precipitation. Since 1877, when weather records began, El Niño events have occurred every three to five years. During recent decades, they have occurred more frequently and have been of several years duration. The El Niño event which began in 1990 and lasted until 1995 was the longest on record.

ENSO influences climate in distant regions (via so-called "teleconnections"). This has been evidenced, for example, by consistent changes in precipitation in specific areas of the globe. Droughts in south-east Asia, parts of Australia, and parts of Africa, and heavy rainfall and flooding in arid areas of South America, have been observed during El Niño years. The Indian summer monsoon sometimes also weakens. In temperate zones, ENSO is associated with mild winters over western Canada and parts of northern USA, and wet winters over southern USA. Worldwide, disasters triggered by drought are twice as frequent during El Niño years than during other years. ENSO events also have a significant economic impact on developing countries in the tropics, primarily through their effects on food production.

Sources: Arntz & Fahrback, 1991; Glantz, Katz & Nicholls, 1991; Yasunari, 1991; Latif & Neelin, 1994; Dilley & Heyman, 1995.

The El Niño/Southern Oscillation (ENSO) is an example of a natural irregular climate fluctuation that involves extensive interaction between atmosphere and ocean. It causes changes in the prevailing winds and the flow of warm ocean surface-waters across the Pacific Ocean, and is second only to the seasonal cycles in its impact on regional climate variability (see Box 2.2) (Aceituno, 1992; WMO/UNEP, 1992a). ENSO events also influence climate in distant regions of the globe.

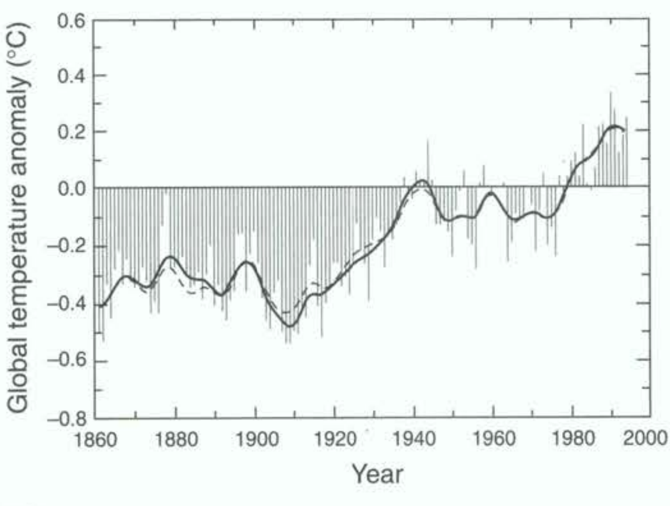
Climate change and greenhouse gases

Climate observations

Historical climate observations indicate how the climate system has responded to varying atmospheric GHG concentrations. Evidently, caution is needed in extrapolating directly from such observations to present conditions since variations might have occurred simultaneously with respect to the intensity of solar radiation, or other components of radiative forcing. Nevertheless, palaeoclimatic measurements from ice cores, dating back 160 000 years, show that changes in Earth's temperature have indeed been closely related to changes in atmospheric GHG concentrations (Jaworowski, Segalstad & Ono, 1992).

Measurements of climate variables on a global scale have been available for approximately a century (Balling, 1993). Fig. 2.2 shows global annual fluctuations in combined land and sea surface temperatures from 1861 to 1994. Global mean surface temperature (land and ocean) has increased by 0.3–0.6°C since the late 19th century, and by 0.2–0.3°C in the last 40 years (Nicholls et al. 1996). With the exception of 1944, the eight warmest years on record occurred between 1983 and 1994. Fig. 2.2 also indicates the high year-to-year variability, even when data are averaged

Fig. 2.2. Combined land and sea surface temperatures 1861–1994, relative to the mean for 1961–1990. The solid curve represents smoothing of the annual values shown by the bars to suppress sub-decadal time-scale variations. The dashed smoothed curve is the corresponding result from IPCC (1992).



Source: IPCC, 1996a.

globally, for the period 1861–1994. Although warming has occurred both at sea and on land, regional and seasonal variation has been observed.

The natural variability of the world's climate makes it impossible to assess precisely the contribution of human activities to climate change (Nitta & Yoshimura, 1993; Woodward & Gray, 1993). But there are indications that human activities account for at least some of the increase in temperature that has occurred over the past century (IPCC, 1996a).

Sources and sinks of greenhouse gases and aerosols

Atmospheric concentrations of several GHGs have been increasing since the beginning of the Industrial Revolution (c.1750–1800), due primarily to human activities such as combustion of fossil fuels. The key GHGs are summarized in Table 2.1 and their relative effects on radiative forcing are shown in Fig. 2.4 (see page 26). Other factors are also important however (see Table 2.2). GHGs accumulate in the atmosphere because of the difference between annual emissions and the capacity of Earth's sinks: that is, the rate at which they are removed from the atmosphere is less than the rate at which they are emitted (Maskell, Mintzer & Callander, 1993).

Carbon dioxide

Although it is known that CO_2 concentrations increased from 280 ppmv in pre-industrial times (c.1760) to 358 ppmv in 1994, uncertainties persist over aspects of the carbon cycle and its component sources and sinks. It is estimated that about 5.5 ± 0.5 GtC per year of carbon emissions result from fossil fuel combustion (and cement production), and a further 1.6 ± 1.0 GtC from changes in land-use in the tropics (especially deforestation) (Schimel et al., 1996). Approximately one-third of human-induced CO_2 emissions is absorbed by forest growth and the oceans; the remainder accumulates in the atmosphere (Kauppi, Mielikaeinen & Kusela, 1992; Sarmiento &

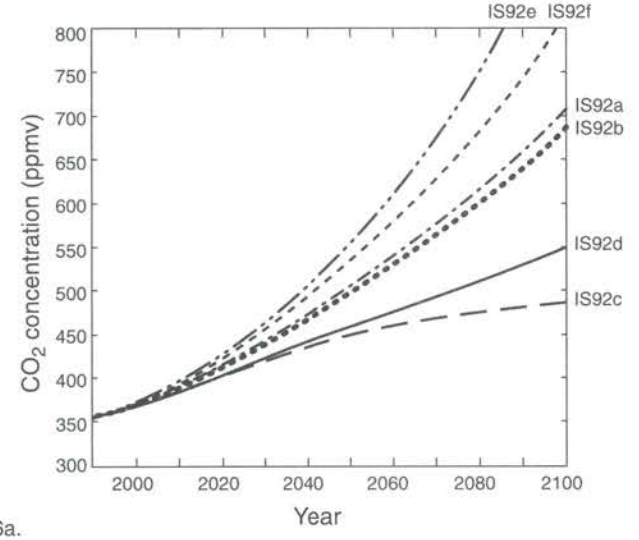
Table 2.1. A sample of greenhouse gases influenced by human activities

	CO_2	CH_4	N_2O	CFC-11	HCFC-22	CF_4
Pre-industrial concentration	280 ppmv	700 ppbv	275 ppbv	0	0	0
Concentration in 1994	358 ppmv	1720 ppbv	312[a] ppbv	268[a] pptv	110 pptv	72[a] pptv
Rate of change in concentration[b]	1.5 ppmv/yr 0.4%/yr	10 ppbv/yr 0.6%/yr	0.8 ppbv/yr 0.25%/yr	0 pptv/yr 0%/yr	5 pptv/yr 5%/yr	1.2 pptv/yr 2%/yr
Atmospheric lifetime (years)	50–200[c]	12[d]	120	50	12	50 000

[a] Estimated from 1992–1993 data.
[b] The growth rates for CO_2, CH_4 and N_2O are averaged over the decade beginning 1984; halocarbon growth rates are based on recent years (1990s).
[c] No single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes.
[d] This is adjusted to take into account the indirect effect of methane on its own lifetime.

Source: IPCC, 1996a.

Fig. 2.3. Projected atmospheric CO_2 concentrations under the full range of IPCC IS92 emission scenarios (see page 30)



Source: IPCC, 1996a.

Sundquiat, 1992). Future atmospheric CO_2 concentrations are calculated using models of the carbon cycle which model the exchanges of CO_2 between the atmosphere and the oceans and terrestrial biosphere (see Fig. 2.3). Atmospheric chemistry models are used to simulate the removal of chemically active GHGs such as CH_4 (IPCC, 1996a).

Methane

The current atmospheric CH_4 concentration is more than double its pre-industrial level. The main sources of CH_4 are rice paddies, animal husbandry, biomass burning and landfills. CH_4 is removed relatively quickly from the atmosphere via oxidation by hydroxyl (OH) radicals and has a relatively short atmospheric lifetime (12–17 years). Because this oxidation reaction produces water vapour, which is also a GHG, the indirect radiative forcing effects of CH_4 are actually greater than its direct effects (IPCC, 1994a).

Nitrous oxide

Since there are many small sources of N_2O, both natural and anthropogenic, quantifying the total N_2O concentration is difficult (IPCC, 1994a). The major anthropogenic sources of N_2O include biomass burning, some industrial processes and the use of nitrogen fertilizers in agriculture. Emissions from natural sources may be twice as high though. Eventually removed by photolytic destruction in the stratosphere, N_2O has a relatively long lifetime in the troposphere (120 years) (IPCC, 1994a). This particular GHG also contributes to stratospheric ozone depletion.

Ozone

Ozone (O_3) acts as a GHG in the middle and upper troposphere, and lower stratosphere. Changes in O_3 concentrations in these layers cause changes in radiative forcing by influencing both solar and terrestrial radiation levels. Nine-tenths of total atmospheric O_3 is found in the stratosphere, with a maximum concentration at an altitude of between 20 and 30 km. Stratospheric ozone is produced by the photolytic destruction of oxygen. Its most important function is to shield life on Earth from ultraviolet radiation (UVR). But in the troposphere, O_3 is a major air pollutant, produced by photochemical reactions of precursor gases such as carbon monoxide, NO_2, CH_4 and volatile hydrocarbons (emitted primarily from combustion engines and natural sources) (Hatakeyama et al., 1991). Ozone concentrations below 8 km in the northern hemisphere may have doubled since pre-industrial times, although ozone distribution in the troposphere is highly variable (IPCC, 1994a).

Halocarbons

Halocarbons are a generic group of human-made chemical compounds that contain carbon and fluorine, chlorine or bromine. They include chlorofluorocarbons (CFCs), are major GHGs, and have long atmospheric lifetimes (more than 100 years). CFCs are destroyed only by photolytic destruction in the stratosphere. They are used for industrial purposes because at ground level they are chemically inert, non-toxic, non-inflammable and odourless. In the last few decades CFC concentrations have increased (with the exception of methyl chloroform). However, growth rates have begun to decline as emission levels are now controlled by the Montreal Protocol and its Amendments (see Box 2.4). Their long lifetimes indicate that atmospheric CFC concentrations will be an important factor with respect to global warming for at least the next century (UNEP, 1993). Hydrochlorofluorocarbons (HCFCs) have a shorter lifetime (about 12 years) than CFCs because they decompose in the troposphere. They have therefore been temporarily permitted as substitutes for CFCs (Rose, 1994). However, they are also potent GHGs and their concentrations are increasing (see Table 2.1) (Schimel et al., 1996).

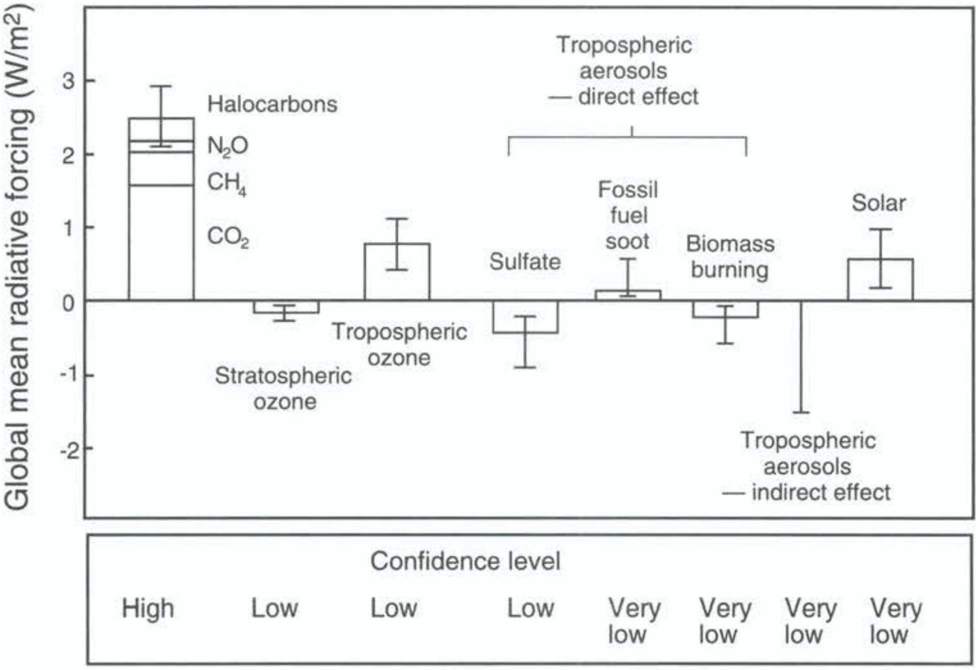
Aerosols

Aerosols are suspensions of particles, ranging in size from 0.001 to 10 µm. Aerosols occur naturally in the troposphere — for example, as dust, evaporated sea salt, or soot. But their tropospheric and

Table 2.2. Sources and sinks of the major greenhouse gases and aerosols

Substance	Sources	Sinks
CO_2	Fossil fuels (oil, natural gas, coal), deforestation, biomass burning, cement production	Ocean and land biosphere
CH_4	Rice paddies, natural wetlands, ruminant livestock, biomass burning, fossil fuels (coal, mining, gas drilling, venting, transmission), termites, animal and domestic waste	Reaction with hydroxyl radicals in atmosphere
N_2O	Biological sources in soils and water, fertilization, biomass burning, industrial sources	Photolytic destruction in stratosphere
Halocarbons (CFCs, halons)	Industrial sources: propellants, refrigerants, foam-blowing agents, solvents, fire retardants	Photolytic destruction in stratosphere
H_2O	Evaporation (ocean), contrails (air traffic), combustion, cooling towers	Cloud droplets, precipitation
Aerosols	Fossil fuel combustion, soot, biomass burning, volcanic activity, soil dust, sea salt, plants	Washed out by precipitation

Fig. 2.4. Estimates of globally and annually averaged radiative forcing (in W/m²) due to changes in concentrations of greenhouse gases and aerosols between pre-industrial times and 1992, and to natural changes in solar output between 1850 and the present



The height of the rectangular bar indicates a mid-range estimate of the forcing while the error bars show an estimate of the uncertainty range, based largely on the spread of published values; the "confidence level" indicates the authors' confidence that the actual forcing lies within this error bar. The contributions of individual gases to direct radiative forcing is indicated by the first bar. The indirect radiative forcing associated with the depletion of stratospheric ozone and the increased concentration of tropospheric ozone are shown by the second and third bars respectively. The direct contributions of individual tropospheric aerosol components are grouped into the next set of three bars. The indirect aerosol effect, arising from the induced change in cloud properties, is shown next; quantitative understanding of this process is very limited at present and hence no bar representing a mid-range estimate is shown. The final bar shows the estimate of the changes in radiative forcing due to variations in solar output. The forcing associated with stratospheric aerosols resulting from volcanic eruptions is not shown, as it varied considerably during this time period. Note that substantial differences occur in the geographical distribution of the forcing due to well-mixed greenhouse gases (mainly CO_2, N_2O, CH_4 and the halocarbons) and that due to ozone and aerosols. For this reason, the negative radiative forcing due to aerosols should not necessarily be regarded as offsetting greenhouse gas forcing.

Source: IPCC, 1996a.

stratospheric levels are also being increased significantly by anthropogenic sulfur dioxide (SO_2) emissions. Tropospheric aerosols influence the radiation balance of Earth in two ways: *directly* by scattering and absorbing radiation, and *indirectly* by modifying the optical properties, amount and lifetime of clouds. Unlike the well-mixed GHGs described above, which are evenly distributed or dispersed, aerosols are very short-lived, with a lifetime of days to weeks, depending on the altitude at which they are emitted into the atmosphere. As a result, tropospheric aerosols tend to be concentrated over and downwind of the regions where they are generated.

The radiative effects of tropospheric aerosols are difficult to quantify because they depend on the distribution, size, shape, and chemical composition of the aerosol particles in question. Moreover, the indirect effects of aerosols also involve complex processes in clouds. Radiative forcing caused by tropospheric aerosols is therefore not as well understood as radiative forcing caused by the well-mixed GHGs. The mid-range estimate for global average direct aerosol radiative forcing due to increases since pre-industrial times in tropospheric aerosol concentrations is -0.5 W/m^2. The indirect aerosol radiative forcing effect for the same time period is estimated to range from 0 to -1.5 W/m^2. Globally averaged radiative forcing due to increases since pre-industrial times in the concentration of well-mixed GHGs is estimated at approximately +2.5 W/m^2 (see Fig. 2.4). Care must be taken when comparing these forcings because the spatial patterns of forcing for aerosols and for well-mixed GHGs are very different. A comparison of global mean radiative forcings therefore does not give a complete picture of their possible climatic impacts. However, in regions where they are concentrated (over and around regions of industrial activity, particularly in Europe and North America, and in areas where considerable biomass burning occurs), tropospheric aerosols are probably offsetting some of the positive radiative forcing of GHGs.

Aerosols are likely to influence future regional climate change greatly. For example, experiments that have considered only the impacts of GHGs, indicate that aerosols reduce warming over and around those regions where they are emitted. But they may also influence climate over wide areas since they may circulate in the upper layers of the atmosphere for a relatively long time. Moreover, since aerosols increase condensation of water vapour, they may also alter precipitation patterns.

Other environmental concerns, such as acid rain, could result in implementation of measures to control emissions of aerosol precursors. Aerosol concentrations would then fall almost immediately, because of their short lifetime. This contrasts with the climatic effects of CO_2 and some other GHGs, which will persist for decades to centuries, even if emissions of these pollutants are reduced substantially in the near future.

Climate scenarios: predictions and uncertainties

When assessing the impacts of climate change on ecological or social systems, a specified future climate change scenario must be used. Climate change scenarios for assessing the impacts of climate change on human health, for example, should (Viner & Hulme, 1994):

- include a sufficient range of climate variables;
- be of a sufficiently detailed spatial scale (because many climate-related health problems occur on a local level) (Robinson & Finkelstein, 1991);
- not be treated as forecasts or predictions, but only as plausible representations of future climates.

Several major types of climate change scenario have been developed, each of which has its own particular advantages and disadvantages.

Arbitrary scenarios

Arbitrary scenarios assume that climate variables change by an arbitrary amount, without any change in their variability. For example, one could assume that temperatures increase by 3°C overall, or that precipitation increases or decreases by 10%. Such scenarios are used to identify the sensitivities of the systems affected to changes in different climate variables. But the arbitrary nature of the changes selected and the lack of attention given to the possible impact of changes in climate variability render extrapolation of assessment results to real-life situations highly problematic.

Analogue scenarios

Use of an analogue scenario entails comparing empirical data from a cool decade with empirical data from a warm decade (see, for example, Vinnikov & Lemeshko, 1987; Rosenberg & Crossen, 1991), or from a particularly warm period with the present (Wigley, 1987). Analogue scenarios provide a clear indication of how regional and local weather patterns change (including changes in variability) during a temporary climate warming. However, in the last fifty years, no climate warming experienced has been equivalent in magnitude or rate of increase to that predicted by the latest global climate models. So the relevance of this methodology to climate change prediction is limited.

Climate model scenarios

Climate model scenarios are dynamic mathematical models that simulate the physical processes of the atmosphere and oceans in order to predict future global and regional climate. General circulation models (GCMs) are the most complex of these models and as such the most powerful tools available for making realistic estimates of climate change (see Box 2.3). However, they involve much uncertainty, especially in terms of estimating regional or local change.

Box 2.3. General circulation models

The most highly developed climate models are atmospheric and oceanic general circulation models (GCMs), often combined to create *coupled* GCMs. They incorporate representations of land surface processes, sea-ice related processes and many other complex processes of the climate system. They are based upon physical laws that describe atmospheric and oceanic dynamics, complemented with empirical data.

GCMs take the form of mathematical equations, which are then solved with computers, using a three-dimensional global grid. For atmospheric GCMs, typical resolutions are about 250 km in the horizontal and 1 km in the vertical, often with higher vertical resolution near the land and ocean surface and lower resolution for the upper troposphere and the stratosphere. Many physical processes, such as those related to clouds and precipitation, take place on much smaller spatial scales, however, and therefore cannot yet be modelled explicitly.

Weather forecasts for periods of up to ten days can be made using atmospheric GCMs. For simulation and projection of climate, however, it is the statistical probabilities of climate events that are of interest, rather than the day-to-day evolution of weather conditions. These include measures of variability as well as of mean conditions. They are calculated for many weather systems and for periods of several months or longer.

If a model is intended to be used for climate prediction, it is first run for many simulated decades without incorporation of any assumptions about changes in external forcing of the climate system. The quality of the simulation can then be assessed and calibrated with observations of the current climate. The model is then run with varying levels of forcing, for instance with different greenhouse gas concentrations. A comparison of current climate with the simulated climate subsequently provides an estimate of the degree of climate change due to changes in forcing factors.

Coupled ocean–atmosphere models are very complex and require large computer resources. They take heat exchange at the ocean–atmosphere interface into account, as well as water–air differentials in the capacity to retain heat. So in order to explore more scenarios under different assumptions, or with different parameter approximations, simpler models are constructed that give global averages similar to those of GCMs. These simplifications may involve coarser spatial resolutions, and the use of simplified dynamics and physical processes, but they are nevertheless useful since they provide a quick and easy means of comparing the effects of different assumptions. (As such, they are not forecasting tools.)

GCMs have several advantages:

- Their mathematical models are designed to estimate accurately how global climate may be affected by changes in radiative forcing.
- Their climate variable estimates are internally consistent.
- They can simulate climate variability over certain specified time-scales, including seasons, and between decades.
- They can provide outputs for a large number of meteorological variables.

However, GCMs have several major limitations:

- They possess low spatial resolution and assume that climate changes are identical for all locations within a grid box. Their estimates pertaining to global and zonal climates appear to be reasonably accurate, but those relating to regional climate are often poor.
- They oversimplify complex physical processes involving the oceans, cloud cover, sea ice, and land surface hydrology.
- The results (of different climate change experiments) often diverge with respect to the degree of temperature or precipitation change estimated for a particular area due to different assumptions and differences in the physical assumptions built into the models.
- Each GCM experiment is a climatic realization of one emissions scenario only, but adapting a GCM so that it represents a range of climate change scenarios is problematic.

Sources: Schneider, 1993; IPCC, 1996a.

Table 2.3. Summary of assumptions in the six IPCC 1992 alternative scenarios

Scenario	Population	Economic growth	Energy supplies
IS92a,b	World Bank 1991 11.3 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	12 000 EJ conventional oil 13 000 EJ natural gas Solar costs fall to US$ 0.075/kWh 191 EJ of biofuels available at US$ 70/barrel[a]
IS92c	UN medium-low case 6.4 billion by 2100	1990–2025: 2.0% 1990–2100: 1.2%	8000 EJ conventional oil 7300 EJ natural gas Nuclear costs decline by 0.4% annually
IS92d	UN medium-low case 6.4 billion by 2100	1990–2025: 2.7% 1990–2100: 2.0%	Oil and gas same as IS92c Solar costs fall to US$ 0.065/kWh 272 EJ of biofuels available at US$ 50/barrel
IS92e	World Bank 1991 11.3 billion by 2100	1990–2025: 3.5% 1990–2100: 3.0%	18 400 EJ conventional oil Gas same as IS92a,b Phase out nuclear by 2075
IS92f	UN medium-high case 17.6 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	Oil and gas same as IS92e Solar costs fall to US$ 0.083/kWh Nuclear costs increase to US$ 0.09/kWh

[a] Approximate conversion factor, 1 barrel = 6 GJ.
Source: IPCC, 1996b.

Emission scenarios

Scenarios of future anthropogenic emissions of GHGs and their precursors, and of the precursors of aerosols, are important inputs for models that project future climates. Future atmospheric GHG concentrations can be calculated on the basis of emission estimates, knowledge of atmospheric chemistry, and global carbon cycle models. Radiative forcing, which is the fundamental output variable of climate models, is linked to GHG concentrations through well-established physical relationships. Increases in radiative forcing due to emission of GHGs can therefore be estimated with some degree of certainty. Changes in radiative forcing due to emission of aerosols can also be estimated, but with less certainty, for the reasons described earlier (page 27).

The key factors that will determine future levels of GHG emissions include population growth, energy demand, the availability of non-fossil fuels, and pressure on forests. (Therefore, in the absence of policies designed specifically to reduce anthropogenic GHG emissions, GHG atmospheric concentrations can be expected to increase.) These various factors are fed into GHG emission scenarios, but obviously, uncertainties abound due to differing assumptions about the future state of the world. Emission scenarios, therefore, should not be viewed as formal predictions of the future. They are, in fact, the most significant source of uncertainty associated with projections of future climate change (Cubasch & Cess, 1990; McBean & McCarthy, 1990; Lindzen, 1993).

The IPCC has defined six emission scenarios: IS92a to IS92f (see Table 2.3) (IPCC, 1994a). The scenarios assume no new policies to reduce GHG emissions and are therefore non-intervention or "business-as-usual" scenarios as far as climate change is concerned. They extend to the year 2100 and incorporate predictions pertaining to emissions of CO_2, CH_4, N_2O, the halocarbons (CFCs and their substitutes HCFCs and HFCs), and of SO_2 from industrial activities and biomass burning. Most published scenarios (including the IS92 scenarios) show an increase in global annual GHG emissions, particularly with respect to CO_2, for the next century. Virtually the only exceptions are scenarios which incorporate either very low population projections or policy measures to reduce GHG emissions.

Components of climate change

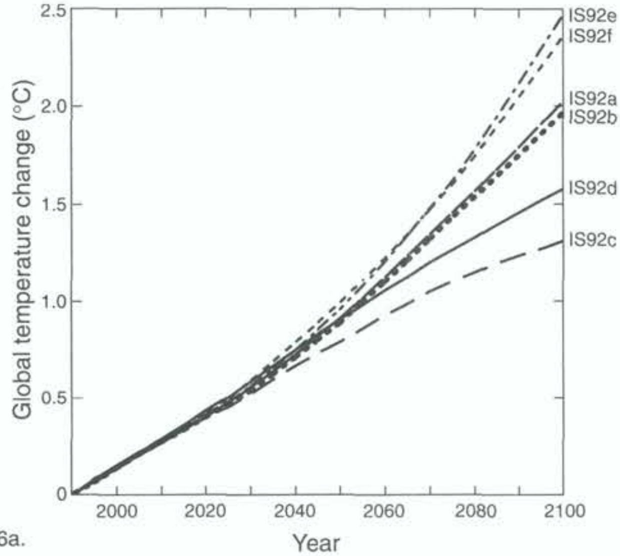
Future changes in climate due to human activities are estimated by first deriving patterns of radiative forcing from scenarios describing potential atmospheric GHG and aerosol concentrations. The detailed climatic response to these patterns of radiative forcing is estimated from GCM experiments (see Box 2.3). However, limited knowledge of the feedbacks operating within the climate system, especially those involving clouds, means that estimates of future climate change contain considerable uncertainty. Moreover, temporal evolution of regional patterns of climate change may depend on variations in the rate of change in radiative forcing and modelling these variations is a complex task. Further uncertainty is associated with the oceans which, because of their large heat capacity, slow climatic response to radiative forcing. It should also be noted that the oceans, through their ability to redistribute heat within the climate system, have an important role in determining the spatial patterns of climate change (see Table 2.4).

Early climate experiments used atmospheric GCMs, coupled to a simple representation of the oceans, to quantify the degree to which future climate may differ from present climate, at double the current CO_2 level, and assuming that GHGs have stabilized and climate response has ceased. (Climate and atmosphere would then be at an equilibrium.) These "equilibrium" climate change experiments serve to determine "climate sensitivity" to CO_2 doubling, taking into account various assumptions concerning the effects of contributory factors. The IPCC assessments of 1990, 1992 and 1995 predicted that the global rise in average temperatures for a doubling of CO_2 levels ("climate sensitivity") is most likely to be in the range of 1.5–4.5°C, with a "best estimate" of 2.5°C. When making projections of future climate change, however, time-dependent climate simulations, or "transient experiments" are also important. Transient GCM climate change experiments are performed over a simulated period of 240 years or more.

Table 2.4. Uncertainties of climate change scenarios

- Emissions of greenhouse gases (dependent on socioeconomic, demographic and political factors)
- Concentration of greenhouse gases (cycles, sources, sinks)
- Sensitivity of clouds to human-made radiative forcing
- Feedback mechanisms (forests, water vapour, clouds)
- Time-scale of climate change due to time-lag caused by the oceans
- Natural variability of climate
- Regional distribution of climate change
- Simplifications and assumptions of GCM simulations
- Frequency and intensity of extreme events
- Effect of polar ice-sheet on sea level rise

Fig. 2.5. Assuming a climate sensitivity of 2.5°C, projected global mean surface temperature change from 1990 to 2100 for the full range of IPCC IS92 emission scenarios



Source: IPCC, 1996a.

The results presented below are a summary of estimates from transient GCM experiments which have been assessed by the IPCC (Kattenberg et al., 1996). A progressive convergence has been observed between the changes observed in global mean temperature, and the changes reproduced in climate change experiments using historical records of GHG build-up, and which take aerosol effects into account (Mitchell et al., 1995). That is, the latest-generation models are able to "predict" the past reasonably accurately. This increases the degree of confidence that can be attached to current GCM projections of future climate change (MacCracken, 1995; Wigley, 1995a).

Changes in global mean temperature

For the central IPCC emission scenario (IS92a) global mean surface temperature is projected to increase by about 2°C by the year 2100 (see Fig. 2.5). When the full range of climate sensitivity (1.5–4.5°C) and the full set of IPCC IS92 emission scenarios are taken into account, climate models project an increase in global mean temperature of between 1°C and 3.5°C (IPCC, 1996a). In all cases the average rate of warming would be greater than any seen in the last 10 000 years, but the actual annual to decadal changes would include considerable natural variability. It is anticipated that with climate change, in most regions and most seasons, night-time temperatures will rise more than day-time temperatures. A small decrease in the global mean diurnal temperature range has in fact been observed (Karl et al., 1993; Kukla & Karl, 1993).

Projected regional climate changes

Results from different climate change experiments suggest that regions will vary in their responses to warming — there may even be areas of cooling. In general, taking GHGs only into account, warming is projected to be greater over land, than over the oceans. Over land, maximum warming is expected to occur at high northern latitudes, particularly in winter. The least amount of warming is estimated to occur over the northern Atlantic Ocean and the Southern Ocean near Antarctica.

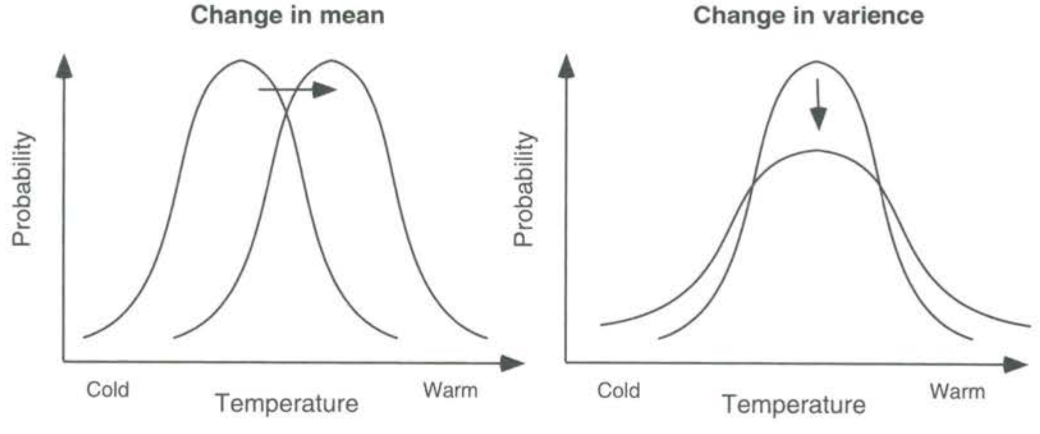
All model results indicate that global average precipitation will increase by about 2% for each 1°C increase in temperature. At high latitudes in winter, for instance in north-west Europe, increases in precipitation are anticipated; most modelling results also show precipitation increases at mid-latitudes, around 45°N or 45°S. But in the dry subtropics (southern Europe and North Africa), it appears that precipitation may decrease, or remain constant. In some regions, therefore, the frequency of dry days, the length of dry spells (consecutive days without precipitation), and the length of the dry season, could increase. This may mean that droughts become longer-lasting and more severe. Conversely, the probability of heavy precipitation events (i.e. more rain per rain-day) is expected to increase, which would have important implications for flooding, groundwater recharge, and soil erosion.

Already, at high northern latitudes, observed precipitation appears to have increased and snow cover decreased, in line with observed temperature increases (Nicholls et al., 1996). Increases in river-flow have also been observed in northern Europe and the USA (Weijers & Vellinga, 1995).

Climate variability and extreme weather events

The predicted impacts of climate change are particularly dependent upon estimates of changes in climate variability and the occurrence of extreme weather events, such as temperature and precipitation extremes, and severe tropical storms. Changes in the mean value of a climate variable will affect the frequency of climate extremes, whether an unchanged or a broadened frequency

Fig. 2.6. Schematic illustration of possible changes in the frequency distribution of temperature



Source: Maskell, Mintzer & Callander, 1993.

distribution applies (see Fig. 2.6). This relationship is non-linear. Small changes in mean climate or climate variability could thus produce relatively large changes in the frequency of extreme events. The frequency of extreme events, however, may reflect changes in variability rather than changes in mean values (Katz & Brown, 1992). The precise impacts of extreme weather events, which can be defined as infrequent meteorological events that have a significant impact upon the society or ecosystem at a certain location, will of course depend not simply on the magnitude of the event *per se*. It will also depend on the vulnerability of the particular natural environment and/ or human society to the magnitude of the deviation from mean meteorological conditions.

No clear evidence has yet been found that sustained or worldwide changes in climate variability or the frequency of extreme events have occurred during the past century. However, regional changes in climatic variability have been observed. For example, there is evidence of an increase in the number of extra-tropical cyclones that have occurred over the North Atlantic (Nicholls et al., 1996). But current assessment of climate variability often suffers from poor data coverage and lack of homogeneity. Future assessment should therefore pay particular attention to the quality of information about the climate parameter in question, the time-scale and the region of interest. A global climate observing system for systematic climate monitoring would contribute significantly to such assessment (see Chapter 9)(WMO, 1994).

Temperature extremes

Most GCM simulations, provided current definitions are maintained, show an increase in the frequency of very hot days and a decrease in the frequency of very cold days. It should be reiterated that predicting climate variability is difficult and beset with uncertainty.

Asian monsoon

The anticipated impact of climate change on areas affected by the Asian monsoon is uncertain. Recent GCM results indicate that mean monsoon precipitation over the south Asian monsoon region may intensify with increased CO_2. This is because the south Asian land area would warm more rapidly than the Indian Ocean, producing a more pronounced land–sea temperature contrast, and hence stronger currents of humid air, leading to greater precipitation over continental areas (Meehl & Washington, 1993).

El Niño/Southern Oscillation

In the tropics, interannual climate variability is associated primarily with ENSO events (see Box 2.2). The ENSO phenomenon is also of special interest since it is linked to precipitation patterns in the Pacific region, and to climate anomalies around the world. Thus as well as affecting tropical cyclone behaviour, ENSO also affects the occurrence of floods and droughts in many regions. However, ENSO events are as yet poorly modelled by GCMs. Moreover, the possible impacts of climate change on the long-range effects of ENSO have not yet been clarified in detail (UNEP, 1992). ENSO events are therefore a significant source of uncertainty in assessments of future changes in climate variability (Viner & Hulme, 1995). Nevertheless, model simulations with coupled ocean–atmosphere models do show an increase in the frequency of ENSO-like events (see, for example, Knutson & Manabe, 1994; Tett, 1995). And although there is little evidence of changes in the frequency or intensity of ENSO events to date, some alterations to effects associated with ENSO may already be occurring (UNEP, 1992; Kattenberg et al., 1996).

Wind storms

Not all the results of model experiments predict global systematic change in storminess for a warmer world. Regional systematic changes cannot be excluded, however. Changes at a local level can probably be anticipated, but the low-resolution GCMs currently in use are unable to simulate extreme events, such as very heavy precipitation, hurricanes and tornadoes, since not only do these occur on a small scale, but they are also rare. GCMs are able, though, to simulate the strength and position of observed storm tracks: experiments indicate a northerly shift in North Atlantic storm tracks.

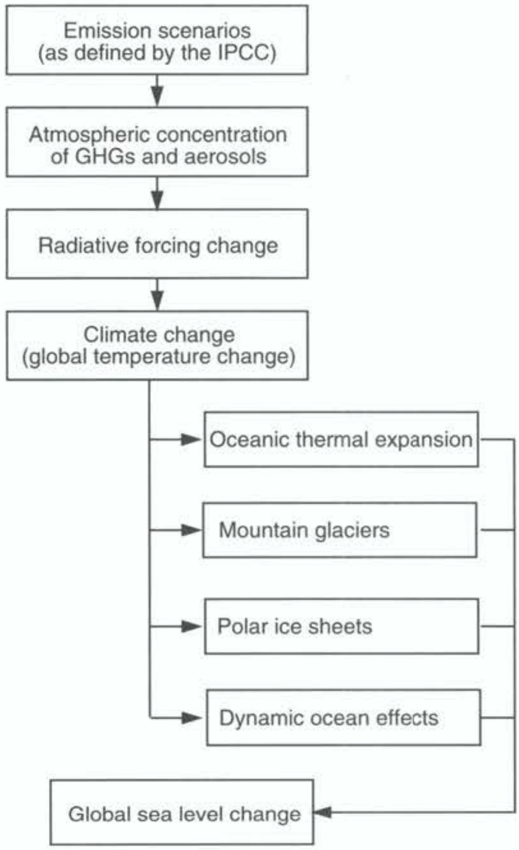
Tropical cyclones affect certain regions of the globe only. They derive their energy from the warm tropical oceans, and occur only when sea surface temperature exceeds 27°C (Evans, 1993). To date there is no strong evidence that increases in sea surface temperature above this threshold would lead to more frequent or more intense tropical cyclones. Furthermore, GCMs may not represent tropical cyclones adequately (Lighthill et al., 1994; Viner & Hulme, 1995; Bengtsson, Botzet & Esch, 1996). Some GCM simulations show increases in "tropical disturbances" which relate to tropical cyclone behaviour, and increases in cyclone frequency and intensity (Broccoli & Manabe, 1990; Haarsma, Mitchell & Senior, 1993). In regions where sea surface temperature ranges between 26°C and 29°C there may in fact be some potential for changes in cyclone intensity (Kattenberg et al., 1996). If changes in tropical cyclone frequency due to climate change do occur, they may be small in comparison to their observed natural variability which is considerable (Lighthill et al., 1994). Climate change could also affect the intensity and location of strong mid-latitude cyclones. In one GCM experiment, cyclonic activity increased significantly at middle and high latitudes (Kattenberg et al., 1996).

Sea level rise

Climate change would cause a rise in sea level, mainly as a result of thermal expansion of the oceans, and also due to melting of mountain glaciers, following an increase in mean global temperature (see Fig. 2.7) (Warrick et al., 1996). For the IPCC central emission scenario (IS92a), global mean sea level is projected to rise by half a metre by the year 2100. Taking into account the ranges in the estimate of climate sensitivity and ice melt parameters, and the full set of IS92 emission scenarios, the models project an increase in global sea level of between 13 and 94 cm by the year 2100. Even if GHG concentrations are stabilized, sea level rise is expected to continue for several centuries. Some concern has been expressed that the West Antarctic ice sheet could disintegrate gradually in a warmer climate, causing significant additional sea level rise. The IPCC 1995 assessment confirms, however, that this is a remote possibility only, although the specific circumstances under which such an event may occur are not known. (The ice sheet survived intact during the previous, warmer, interglacial of 100 000 years ago.)

Changes in future sea level would not occur uniformly around the globe. Recent model experiments suggest that regional responses could diverge from the mean by a factor of between 2 and 3, due to regional differences in atmospheric heating and large-scale changes in ocean circulation. Additionally, variation in the geological and geophysical processes that cause vertical land movement would contribute to variation in local and regional sea level changes. If the baseline sea level rises, the risk of coastal flooding will increase. The populations most vulnerable to sea level rise would be those of densely-settled deltas and small islands (see Chapter 7).

Fig 2.7. Climate change and sea level rise components incorporated in projections of changes in global mean sea level



Source: Warrick, 1993.

Other impacts

Questions are often asked about the long-term stability of climate and whether large, virtually discontinuous changes could occur as a result of increasing GHG concentrations. A potential change relates to the circulation of the ocean and currents such as the Gulf Stream, which maintains the North Atlantic at a temperature several degrees higher than it would otherwise be. Several experiments using complex climate models indicate that large-scale ocean circulation might weaken with global warming. That is, the difference between atmospheric temperatures at the equator and those at higher latitudes — which constitutes the "motor" of trade winds — might decrease. Climate observations indicate that such a change might already have taken place during the last few decades. Furthermore, climate model experiments and the study of palaeoclimatic records both demonstrate that transitions to quite different circulation patterns could occur fairly rapidly. The probability of such events arising in response to global warming, and the degree of radiative forcing at which the change would be significant, are currently subjects of much scientific debate.

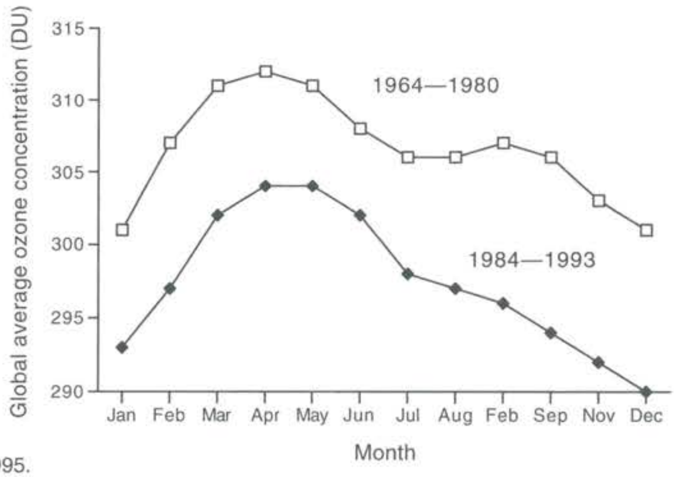
Stratospheric ozone depletion

Stratospheric ozone is thought to have begun forming several billion years ago (approximately halfway during Earth's history), as a result of the solar-powered destruction and recombination of oxygen. This oxygen was, in effect, a "waste product" produced by the photosynthetic activity of the newly-evolved green plants. The natural concentration of stratospheric ozone is now maintained through the dynamic equilibrium existing between production and destruction of ozone. The latter reaction is catalyzed by trace amounts of hydrogen, nitrogen and halogen free radicals (particularly chlorine and bromine). These radicals occur naturally, but in recent decades their concentration has been increased greatly by industrial activities. This has upset the aforementioned equilibrium and led to a sustained decline in stratospheric ozone concentrations (Molina & Rowland, 1974; WMO et al., 1994).

The excess halogen free radicals derive from halocarbons — in particular CFCs and halons. These human-made gases have been used extensively as refrigeration fluids, blowers in foam-making, aerosol propellants, solvents, and in fire extinguishers. In general, bromine-containing compounds and bromine radicals are much more destructive of ozone than are chlorine radicals. Methyl bromide is another ozone-destructive gas, the emissions of which have also risen considerably due to human activity (Butler, 1995).

Significant stratospheric ozone losses have occurred mainly at middle and high latitudes. The rate of ozone depletion depends upon both the season and latitude (Fig. 2.8). Thus ozone depletion is more pronounced in winter and spring than in summer (UNEP, 1994a). Additionally, these seasonal differences are more marked in the northern hemisphere than in the southern hemisphere (with the exception of Antarctica), although ozone depletion is in general more pronounced in the southern hemisphere.

Fig. 2.8. Monthly global average stratospheric ozone values show substantial declines in the period 1984–1993, especially strong in September–January months, compared with 1964–1980 levels. Since the global averaging includes the huge surface of the equatorial belt where no significant changes occurred, the actual decline in extratropical latitudes was much larger.



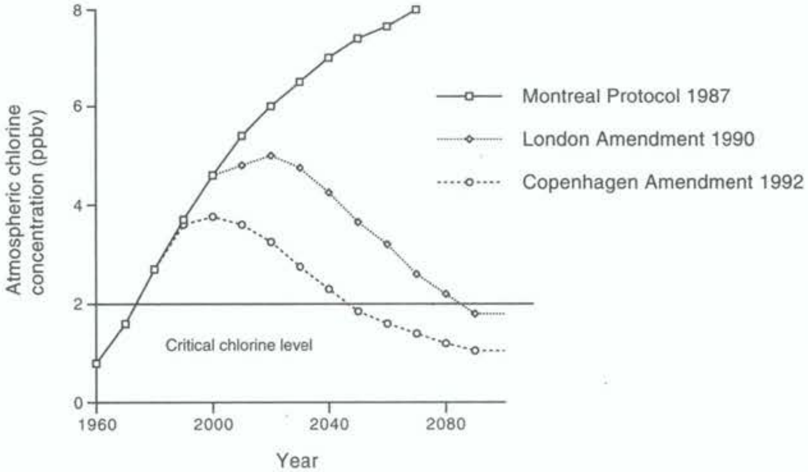
Source: Bojkov, 1995.

Box 2.4. Ozone Convention and Protocol

Since the early 1980s the threat posed by various human activities to stratospheric ozone has became more and more evident. The international community has responded by adopting the Vienna Convention for the Protection of the Ozone Layer, concluded in 1985. This convention provided the foundation for the Montreal Protocol of 1987 on "Substances that Deplete the Ozone Layer". This was the first step taken towards controlling and reducing the production and use of the more destructive forms of halocarbons. However, research and monitoring indicated the necessity of more stringent cuts in halocarbon use in order to stabilize and enable eventual recovery of ozone concentrations. The Parties to the Protocol therefore agreed to the London and Copenhagen Adjustments and Amendments, in 1990 and 1992 respectively, aimed at phasing out use of most ozone-depleting substances by 1 January 1996.

If strict compliance is achieved internationally, concentrations of chlorine in the atmosphere, and hence ozone damage, should peak within the next decade or so. Maximum ozone losses, relative to the late-1960s are likely to be 12–13% at northern mid-latitudes in winter and spring, about 6–7% at northern mid-latitudes in summer and autumn, and about 11% at southern mid-latitudes. WMO estimates that these changes will be accompanied by 15%, 8% and 13% increases respectively in ground-level ultraviolet radiation, sufficient to cause erythema, if other factors, such as clouds, remain constant . It is anticipated that these peak levels will persist, with little decline, for several decades, reflecting the long lifetime of chlorine radicals in the stratosphere. Subsequently, recovery of stratospheric ozone is expected to occur by replenishment, to the extent that 1990 levels of ozone will be regained by the middle of next century.

Estimates and projections of stratospheric chlorine loadings from the 1960s to the year 2080, assuming full implementation of the control measures introduced by the 1987 Montreal Protocol and its 1990 and 1992 Adjustments and Amendments



Sources: Armstrong, 1994; UNEP, 1993; 1994a.

The most dramatic instance of ozone depletion is known as the "ozone hole". It appears over Antarctica in spring and amounts to an overall ozone loss of more than 40%, and has done since the 1970s (Bojkov, 1995). The ozone hole is attributable to chemical processes that occur on the surface of the particles of polar stratospheric clouds. The formation of polar stratospheric clouds requires temperatures below -80°C; these occur more frequently in the Antarctic than in the Arctic (Kerr, 1992). With the arrival of sunlight in spring, UVR forms free radicals via photolytic destruction of halogens and N_2O, which then destroy ozone catalytically (Molina & Rowland, 1974). The size of the ozone hole continues to increase (Jones & Shanklin, 1995). Indeed, the rate of overall ozone depletion has risen during the 1990s. Ozone losses over the Arctic are less distinct, but there are now well-established ozone depletion trends in both hemispheres.

Stratospheric ozone shields Earth's surface from incoming solar UVR which is harmful to animals and plants (see Chapter 8). Thus a decrease in stratospheric ozone is anticipated to increase UVR at the mid-latitudes of both hemispheres. Indeed, increases in ground-level UVR have been observed recently, as has an increase in UV-B of $7 \pm 4\%$ per decade in the Swiss alps, 3576 m above sea level (Madronich et al., 1995). It should be noted that the intensity of UVR actually reaching Earth's surface depends on the total amount and vertical distribution of certain trace gases and industrial aerosols, and climatic conditions such as mean cloud cover. In the northern hemisphere, in some industrialized areas that experience high air pollution levels, small decreases in UV-B have been observed, presumably a result of the scattering processes of aerosols and absorption by tropospheric ozone.

A phasing out of CFCs and other halocarbons was agreed to internationally in the Montreal Protocol and its London (1990) and Copenhagen (1992) Adjustments and Amendments (UNEP, 1993). Nevertheless, the concentration of stratospheric ozone is not expected to return to its normal level until the second half of the next century (see Box 2.4).

Stratospheric ozone depletion and climate change

Climate and weather are often thought to be a product of the *lower* atmosphere — that is, the troposphere. Hence, to include a chapter about the depletion of ozone in the stratosphere, or middle atmosphere, in a book about global climate change may seem inappropriate. But there are several links between stratospheric ozone depletion and climate change (Rind & Lacis, 1993; WMO et al., 1994). These include the following:

- Several of the GHGs, especially CFCs, produce radicals that also destroy ozone. (Ozone is itself a GHG.) Ozone depletion has caused the stratosphere to cool by between 0.6°C and 0.8°C during the past two decades. It is estimated that ozone depletion in the lower stratosphere may have offset 15–20% of the positive radiative forcing that has occurred in recent decades (Bojkov, 1995). (Levels of tropospheric ozone have nevertheless increased.)
- Temperature changes in the lower atmosphere may influence the formation of ozone and ozone-depleting radicals and hence the chemical composition of the stratosphere, as well as the overall atmospheric heat budget.
- Moreover, increased UV-B in the lower atmosphere influences the production of photochemical oxidant pollutants such as tropospheric ozone, and, via the enhanced formation of OH radicals, may reduce the concentration of tropospheric methane and increase the formation of clouds (which reflect away incoming solar energy) by increasing the production

of sulfate nuclei from SO_2 (Bekki, Law & Pyle, 1994; Isaksen, 1994; Toumi, Bekki & Law, 1994).

- Ground-level UVR, while determined primarily by the extent of stratospheric UV absorption, is reduced by clouds and air pollution in the troposphere. As both are temperature-dependent, climate change may affect ground-level UVR.
- Some aspects of global environmental change relevant to human population health, such as changes in agricultural productivity and infectious disease transmission, are being influenced by changes in both the troposphere and stratosphere. For example, the adverse impact upon crop yield of increased exposure to UV-B is related, interactively, to ambient temperature through effects on photosynthesis, and plant sensitivity to diseases and damage by pests (Kendall & Pimentel, 1994).

Climate change mitigation

The variety and extent of interaction between human society, ecosystems and climate render climate change a major and unusual challenge for science and environmental health policy-makers. But although scientific evidence of the risk of an enhanced greenhouse effect has been growing for many decades, it was not until the mid-1980s that sufficient political will was generated in favour of global assessment of this hazard, and research efforts into mitigation initiated. Thus the IPCC was not created until 1988; subsequent adoption of the UNFCCC in 1992 was one of UNCED's major achievements (see Box 2.5). However, even if implementation of effective mitigation measures, on the basis of internationally agreed protocols and publicly accepted practices does not occur for some time, the arsenal of technologies for risk assessment and mitigation is growing rapidly.

In principle, mitigation measures fall into two broad categories: the control of GHG sources, and the enhancement of GHG sinks. Although CO_2 emissions exceed those of other GHGs, the relative global warming potentials of other GHGs (principally CH_4 and N_2O) are sufficiently high to justify their inclusion in international mitigation programmes.

The IPCC has assessed the various mitigation options that have been proposed in recent years (IPCC, 1996b). If mitigation measures are instituted, several sectors in particular — namely, agriculture, rangeland and forest management, energy supply and demand, and consequently manufacturing industry — would be obliged to modify many of their operating procedures. The IPCC assessment report highlights the following "common themes" and "conclusions" pertaining to mitigation measures:

- An extensive array of technologies and policy measures for mitigating GHG emissions is available. Current social, institutional, financial, market and legislative barriers limit their application, however. Their realized potential is therefore often significantly less than their technical potential.
- Actions to reduce GHG emissions are likely to be easier to implement if they are designed simultaneously to address other factors that impede sustainable development. They will be more effective too if they incorporate well-integrated combinations of policies, tailored for local situations and developed through consultation with stakeholders.
- Continued commitment to research is essential if technologies are to be developed that will lead to a significant reduction in GHG emissions.

Box 2.5. UN Framework Convention on Climate Change

A total of 156 States have now ratified the UN Framework Convention on Climate Change (UNFCCC), initiated at the United Nations Conference on Environment and Development in 1992. Governments that are Parties to the Convention are seeking to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

The Convention emphasizes that:

- developed countries are primarily responsible for historic and current emissions and must take the lead in combating climate change;
- the first priority of developing countries must be their own economic and social development;
- the share of total global emissions of developing countries will increase as they industrialize;
- states that are economically dependent on coal and oil will face special difficulties if mitigation measures oblige them to limit their use of these forms of energy;
- countries with fragile ecosystems, such as small island states and arid countries, are particularly vulnerable to the anticipated impacts of climate change.

By becoming Parties to the Convention, both developed and developing countries agree to:

- submit for review information about the quantities of greenhouse gases (GHG) that they emit, by source, and about their national "sinks" (notably forests and oceans);
- carry out national programmes for mitigation of and adaptation to climate change;
- strengthen scientific and technical climate system research and systematic observation, and promote the development and diffusion of relevant assessment and mitigation technologies;
- support education programmes concerning climate change and its likely effects, and work to increase public awareness of the climate change issue.

Developed countries accept a number of additional commitments specific only to them, including:

- Adoption of policies designed to limit their GHG emissions and to protect and enhance their GHG "sinks" and "reservoirs". They have announced that they will seek to return to their 1990 emissions levels by the year 2000. They will also submit detailed information on their progress. The Conference of the Parties will review the adequacy of this commitment and actions pertaining to it at least twice during the 1990s.
- Transfer of financial and technological resources to developing countries, over and above that which is already available through existing development assistance, and support to those countries seeking to meet their commitments under the Convention.
- Provision of aid to developing countries that are particularly vulnerable to the adverse effects of climate change so that they can meet the costs of adaptation.

Continued on next page.

Box 2.5. continued.

In Berlin, in March 1995, the first Conference of the Parties (COP-1) to the UNFCCC took place. The following agreements were negotiated:

- Article 2: it was concluded that the stabilization aim of the UNFCCC (i.e. reduction of emissions to 1990 levels) is inadequate and a process that leads to appropriate action for the period beyond 2000 (i.e. quantified limitation and reduction objectives for all GHGs) should be agreed upon by 1997.
- Joint implementation: a pilot phase before the end of the decade is recommended for activities implemented jointly.
- Technology transfer: the UNFCCC secretariat will report at the Second Conference of the Parties (COP-2) in 1996 on concrete measures taken by the Parties on this issue.

COP-2 is scheduled to take place in Geneva in July 1996.

Source: UNEP/WMO, 1992.

As pointed out by Gates (1993), the potential economic consequences of most of the measures proposed for controlling GHG emissions has stimulated the search for technological "fixes" that would reduce radiative forcing without entailing major adjustment to the current energy-intensive foundations of economic growth. Suggestions made to date include the placement of huge mirrors in space to reduce incoming solar radiation, the introduction of artificial cloud condensation nuclei in the atmosphere to increase planetary albedo, iron fertilization of parts of the Antarctic Ocean and the equatorial parts of the Pacific to increase CO_2 sequestration in the world's oceans, and the absorption of flue gas CO_2 from smoke stacks by chemical means. Not only do these measures not call for changes in current levels of energy use, but they are highly energy-intensive themselves. They are also impractical for the foreseeable future. Moreover, as is true for all proposed mitigation measures, large-scale implementation should not be attempted before assessment has been undertaken of the risks they could pose to the environment and human population health.

Chapter 3

Heat, cold and air pollution

Conventional climate–health research

This chapter describes some of the research that has been undertaken to investigate the effect of natural climate variability upon human health. The results of this research have provided much of the information used to predict the future health impacts of changed patterns of thermal stress (especially heat waves). Methods for studying the potential health impacts of future global climate change are discussed in more detail in Chapters 9 and 10.

Human sensitivity to climate

The biology and health of human populations are influenced not only by climate conditions but also by the way in which the surrounding habitat affects climatic variables such as temperature, wind speed and humidity. Thus the presence of mountain ranges can affect local temperature and provide protection from high wind speeds, while the presence of water bodies such as oceans, lakes and rivers may increase humidity. Similarly, the absence of vegetative cover may decrease humidity.

Human physiological adaptive activities, such as sweating, and degree of comfort are determined largely by climatic factors. However, in the indoor environment, modifying factors such as heating and air-conditioning may influence considerably the atmospheric conditions to which humans are exposed. Individual lifestyles, clothing habits and occupational conditions also influence the exposure levels of people otherwise sharing the same habitat.

Climate also acts on human health and survival indirectly through its effects on ecosystems, on the hydrological cycle (water supply), on food species, and on disease agents and vectors. While scientific records of the indirect health impacts of climate are few, a wealth of information on human tolerance levels and physiological responses to climate factors has been collected by biometeorologists.

Within certain ranges of tolerance, human biology can handle most variations in climate, whether these relate to rate of change or degree of change. But marked short-term fluctuations in weather can cause "acute" adverse effects. These are often indicated by increased death rates, upswings in hospital admissions, and increases in the number of individuals complaining of mental stress such as depression.

Research in China, Canada, Egypt and the USA, supports the "range of tolerance" concept (Rogot & Padgett, 1976; Jones et al., 1982; Kalkstein & Smoyer, 1993). For example, in China, only the warmest 10–15% of all days in summer have an impact on human mortality (Tan, 1994). Similarly, for both New York City, USA and Shanghai, China, a sharp increase in the numbers of daily deaths is observed once temperature exceeds a certain threshold. But the health impact of climate variability varies markedly across regions. For example, only those cities in the north and midwest of the USA and China appear to show a strong climate–mortality relationship (Kalkstein & Davis, 1989).

Evidence also exists that long-term (i.e. monthly and annual) fluctuations in weather affect human health (see, for example, Sakamoto & Katayama, 1971). Some studies have even concluded that interseasonal and intraseasonal variation may have greater impacts than does daily weather variability (Sakamoto, 1977; Persinger, 1980). In the northern hemisphere, during summer, June heat waves are associated with a much higher mortality rate than August heat waves of similar magnitude. Such variation in population health impact within a single season has two possible explanations. Firstly, the most susceptible members of the population may die during the early heat waves. Secondly, those who survive the early heat waves may become behaviourally or biologically acclimatized, and hence able to deal with later heat waves more effectively (Marmor, 1975). Alternatively, both explanations may apply (Kalkstein, 1993). These explanations may also be applicable to health problems, such as asthma and influenza, which may decline in incidence as stressful weather continues (Antó & Sunyer, 1986).

People living in hot regions, such as the southern USA or southern China, cope with excessive heat through adaptations in lifestyle, physiological acclimatization and adoption of a particular mental approach (Ellis, 1972; Rotton, 1983). Cultural or social adjustments, including design of houses for conditions of sustained heat, may also explain why mortality rates in hotter climates remain stable. But in temperate regions, periods of excessive heat occur less frequently, and populations accordingly have a smaller repertoire of behavioural, social and technical adjustments.

Climate variables relevant to climate–health research

The conclusions of studies of the climate–health relationship depend much upon how the meteorological data are used. Two issues are of particular relevance. A choice must be made between single-variable and composite-variables analyses, and it must be recognized that the main measures of weather/climate, such as daily maximum temperature, account only partially for the impact of climate and weather on biological organisms and systems. Box 3.1 illustrates some of the problems associated with use of climate data in studies of health impacts.

Evidently, humans and other organisms react to the particular configuration of coexistent climate variables of their immediate environment. Researchers therefore use climatological indices that combine individual climate variables in a way that maximizes their relevance to human health (Lowry, 1988). For example, "wet-bulb" and "dry-bulb" temperature readings, which enable relative humidity to be assessed, can be combined with temperature to create a more health-relevant index. Other commonly used composite indices include: human comfort indices; heat budgets; and synoptic climatological classifications.

Human comfort indices and the heat-budget model

Although several types of index have been developed to measure winter discomfort, the majority of human comfort indices evaluate the impact of heat stress on the individual, taking into account temperature, humidity, or a combination of the two (Court, 1981, 1983; Quayle & Doehring, 1981).

Box 3.1. Good and bad practice in handling climate data

Examples of appropriate use of climatological data for health impact analyses are given below:

- *Long and continuous records with short time intervals.* Noteworthy trends, whether seasonal or irregular in nature, can be evaluated and the influence of weather variations ascertained more effectively if the time increment between data collection times is short compared with the time-scales of the changes studied. For example, the daily blackfly population counts collected by WHO's Onchocerciasis Control Programme are among the best for climate health analyses owing to the regularity and frequency of collection. In another research area, population-wide death records collected on a daily basis can be effectively analysed against sets of daily weather characteristics in studies on heat-related mortality. The benefits of using this kind of record is particularly relevant in the study of *threshold* levels. The relationship between many health variables and climate exhibits an actual threshold.
- *Climatic water-budget models.* The water-budget approach enables evaluation of the moisture exchange that occurs between Earth's surface and the atmosphere. It has important potential for climate impact research, for example, in assessing vector-borne diseases. Water-budget evaluation is particularly suited to estimating mosquito and blackfly populations since the population dynamics of these two insect families are influenced differently by water velocity in the larval habitat.
- *Heat-budget models.* The heat-budget approach evaluates the thermoregulation that occurs through heat income and loss. Each of these is affected by climate variables. The quantitative estimates of water and heat exchange obtained through budget models are superior to those obtained via the analysis of individual meteorological variables.

The following approaches to the use of climatological data for health impact assessment should be applied with caution:

- *Raw meteorological variables.* Treating temperature, humidity, wind speed and other meteorological variables as separate variables in multiple regression analysis (with a health parameter as the dependent variable) ignores the natural associations between weather elements, the combined effect of which may be the most important influence upon human health.
- *Reliance on means (e.g. mean July temperature, mean annual precipitation).* Means de-emphasize the importance of extreme situations. Yet in terms of weather, extreme events have the greatest direct impact on human population health. If an *overall* mean is used to describe possible long-term changes in climate, the importance of extreme situations is de-emphasized even further.
- *Use of "running means".* Running means, averaged over consecutive days, are used to uncover long-term trends or cycles. However, they "dampen" the extremes which might particularly influence human health. Running means also create an artificial lag within a data set, which might alter the interpretation. Use of "harmonic" and other analyses is recommended for overcoming this problem.

Sources: Mather, 1985; WHO, 1985; Mather, 1993; Mills, 1995.

Box 3.2. Historical climate data for health studies

Data can be obtained from many sources for use in health effects studies. Most countries have a central meteorological agency that stores climate data, usually in digital form. Systematic data on health outcomes, especially mortality, can be obtained from national health and vital statistics agencies. Details on time, location and cause (at least for deaths) should also be available.

Historical climate data can be obtained from two sources. First-order weather stations possess the most complete records, and usually the longest time series. These records include hourly readings for air temperature, dewpoint temperature, relative humidity, cloud cover, wind speed, wind direction, surface air pressure, and often precipitation, and sometimes even vertical soundings. These are the meteorological data of choice for most health effects evaluations, and such data are becoming increasingly available on CD-ROM.

The second source is the cooperative weather station. These are run by volunteers, and thousands of such stations exist worldwide. For local climate–health impacts analysis, a cooperative station may well be available close to the actual location where health data are collected. Cooperative weather stations typically provide daily maximum and minimum temperature readings, as well as total daily precipitation. A few possess specialized equipment such as solar radiation sensors and evaporation pans. The network of cooperative weather stations is much denser than that of first-order stations. But the information provided is less detailed, of shorter duration and often less complete.

The most common winter comfort index is "wind chill", developed in the 1940s (Siple, 1945). Wind chill is defined as the quantity of heat that the atmosphere is capable of absorbing from an exposed surface one metre square, in one hour. This measure reflects the potential for heat loss to the atmosphere from a surface such as the human body under specific combinations of wind speed and temperature. A similar "wind chill equivalent temperature" can be obtained from different combinations of air temperature and wind speed (a 0°C temperature combined with a wind speed of 15 mph yields the same wind chill temperature as a -9°C temperature combined with a wind speed of 5 mph). These two particular combinations would result in the same level of human discomfort. The original wind chill index assumed that the subject was not clothed. Steadman (1984), however, considered the impact of wind chill on appropriately dressed individuals. His wind chill equivalent temperatures (Table 3.1) are therefore higher than Siple's for a given combination of air temperature and wind speed, and generally considered more realistic.

The most commonly used summer index is the temperature–humidity index, which incorporates air temperature and relative humidity (Table 3.2). Values in the low 20s are associated with little discomfort, while values in the 30s are considered highly uncomfortable. Another commonly used summer index, "apparent temperature" (see below), was developed to evaluate physiological human responses to various weather conditions (Steadman, 1984). A simplified algorithm to define apparent temperature uses air temperature, vapour pressure, and wind speed for indoor locations, shaded locations, and sunny locations (Kalkstein & Valimont, 1986).

Table 3.1. Windchill equivalent temperatures (°C) from Steadman's formula: a measure of winter comfort which considers the loss of heat from the human body under varying combinations of wind speed and temperature

	Wind speed (km/s)						
Temperature	**Calm**	**2**	**4**	**9**	**11**	**13**	**18**
0	1	0	-3	-6	-8	-10	-12
-2	-2	-2	-2	-7	-11	-13	-16
-4	-3	-4	-7	-12	-14	-16	-19
-8	-6	-8	-11	-17	-19	-21	-25
-12	-11	-12	-16	-22	-25	-28	-33
-16	-14	-16	-19	-27	-30	-33	-40
-20	-18	-20	-24	-33	-37	-41	-51
-24	-22	-24	-29	-39	-44	-51	
-28	-26	-28	-33	-45	-51		
-32	-30	-32	-38	-53			
-36	-33	-36	-42				
-40	-37	-40	-48				

Source: Steadman, 1984.

Virtually all the human comfort indices developed to date are "absolute" and assume that a given index value produces identical levels of discomfort at all locations. However, this is not so. A temperature of -12°C combined with a wind speed of 15 mph would be perceived as highly uncomfortable in Rome but rather uneventful in Moscow. Thus "relative" indices have been developed which assume that humans are affected most by weather that is unusual for their particular locale. The best known of these is the weather stress index (WSI), which compares a particular weather event in a particular location to average conditions for the same location at the same time of year, thereby evaluating how unusual that event might be. The WSI is based on apparent temperature and expressed as the percentage of days with apparent temperatures lower than that of the day under review. For example, a WSI of 99% in summer, or a WSI of 1% in

Table 3.2. The temperature–humidity index: a measure of summer comfort that considers the combined effect on the human body of temperature and relative humidity

	Relative humidity (%)									
Temperature °C	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
21	18	18	18	19	19	19	20	20	20	21
24	19	19	20	20	21	22	22	23	23	24
27	20	21	22	22	23	24	24	25	26	27
29	22	23	23	24	25	26	27	28	28	29
32	23	24	25	26	27	28	29	30	31	32
35	24	26	27	28	29	30	31	32	33	35
38	26	27	28	30	31	32	34	35	36	38
40	28	29	30	32	33	35	36	38	39	40

Source: Mather, 1974.

winter, would be quite stressful. However, the real temperature corresponding with a 99% or a 1% WSI will vary according to the time-of-year, locale and degree of acclimatization attained by the persons tested.

Humans react to the atmospheric environment through heat exchange, and they must keep heat production and loss at an equilibrium in order to maintain body core temperature at around 37°C. Factors influencing thermal comfort include air temperature, humidity, wind speed, and fluxes in short-wave and long-wave radiation. The comfort indices discussed above take only the first three factors into account. But a heat-budget model takes into account all mechanisms of heat exchange between the human body and its environment, which are so important in maintaining human comfort (Lowry, 1988; Jendritzky & Sievers, 1989). A number of heat-budget models have been developed (Jendritzky et al., 1990). An application of one such model to mortality data is shown in Fig. 3.2. Comfort indices and heat-budget models represent a considerable improvement over studies that use "raw" meteorological data, and are increasingly used for weather–human health analyses.

Synoptic climatological approaches

Since humans respond to the net impact of all meteorological elements to which they are exposed simultaneously, composite measures can be expected to better predict the effects of the totality of weather on health than would a set of component weather variables treated separately. Synoptic approaches are used frequently by biometeorologists to characterize the surrounding body of air and its qualities as "air masses". These approaches combine a complex set of meteorological variables into one composite characteristic (Perry, 1983; Yarnal, 1993). To date, synoptic approaches have been used for a number of studies in Europe and North America, including studies of atmospheric pollen densities, asthma hospital admissions, biological stresses, human mortality and the impact of climate and climate change on air pollution (Wax, Borengasser & Muller, 1978; Balling, 1984; Muller & Jackson, 1985; Antó & Sunyer, 1986; Sanchez et al., 1990; Kalkstein, 1991a; Schwartz, 1991; Bucher, 1993; Bucher & Haase, 1993).

The occurrence of air masses can be recorded daily and a calendar constructed to determine their frequency and character at a given place (Kalkstein et al., in press a). (Table 3.3 lists the mean meteorological characteristics of 10 summer air masses for St Louis, USA.) Additionally, the impact of many consecutive days or "strings" of stressful air masses can be determined. The air mass-based synoptic approach has been applied successfully to human mortality studies in the USA and Canada (Kalkstein & Smoyer, 1993). For example, in St Louis, one particularly stressful type of summer air mass (category 9 in Table 3.3) is associated with very high mortality. Although this "tropical" air mass occurs on only 7% of the summer days in St Louis, it has been associated with 8 of the 10 highest mortality days on record. Synoptic methods have also been used to identify "weather types" or pressure patterns (rather than air masses) which may relate to variations in human health. For example, Driscoll (1992) correlated areas within a wave cyclone model with altered frequencies of various respiratory and cardiovascular diseases, while Jendritzky and Bucher (1992) performed a similar analysis relating to human mortality.

The synoptic approach has several advantages. It allows a threshold, or a particularly stressful air mass beyond which human health problems appear to increase markedly, to be determined. It enables the impact of weather to be distinguished from other factors that may affect human health.

Table 3.3. Mean meteorological characteristics for the 10 summer synoptic categories in St Louis, USA

Description	Category frequency	Time hr	T[b] °C	T[c] °C	Pressure mb	Cloud cover tenths	Wind[d]
1 Anticyclonic continental	18.7	0700 1900	23 22	13 14	1021 1019	3 2	NE, light
2 Anticyclonic transitional	10.7	0700 1900	26 25	18 18	1020 1018	4 3	SE, moderate
3 Anticyclonic maritime	12.1	0700 1900	26 26	21 21	1018 1016	7 6	SSE, moderate
4 Weak wave overcast	8.7	0700 1900	23 22	19 19	1016 1015	9 7	SW, light
5 Maritime tropical, cloudy	17.4	0700 1900	27 26	21 21	1014 1013	7 6	SW, strong
6 Maritime tropical, sunny	6.5	0700 1900	29 28	21 21	1018 1016	2 3	SSW, strong
7 Continental to maritime transition	10.0	0700 1900	26 24	18 18	1015 1014	5 4	W, moderate
8 Maritime unsettled	2.5	0700 1900	24 23	20 20	1010 1010	9 7	WSW, strong
9 Oppressive tropical (some continental influence)	7.0	0700 1900	30 30	21 21	1015 1013	2 2	SE, strong
10 Continental polar, recent frontal passage	6.4	0700 1900	21 19	14 13	1015 1015	6 3	NW, moderate

[a] Per cent of total days within each category
[b] Air temperature
[c] Dewpoint temperature
[d] Wind direction and speed

Source: Kalkstein, 1991a.

It can also facilitate operation of a watch/warning health system (Pennsylvania Heat Wave Preparedness Task Force, 1994; see also Box 3.7). Moreover, spatial synoptic approaches can track an air mass as it moves across a large area, enabling its potential impact across an entire continent to be monitored (Kalkstein et al., 1993).

Synoptic approaches were little used before the 1980s owing to the difficulty in quantifying the interaction of meteorological variables within an air mass. Automated, objective approaches are now available for categorizing air masses, however, and these represent a great improvement over the subjective synoptic determinations of the past (McCutchan, 1980; Harrington & Harman, 1985; Kalkstein, Tan & Skindlov, 1987; Schwartz, 1991; Barthel et al., 1993; Davis & Gay, 1993). (Synoptic units are composed of measurable sub-units. These are objective as they are not associated with well-being or comfort.)

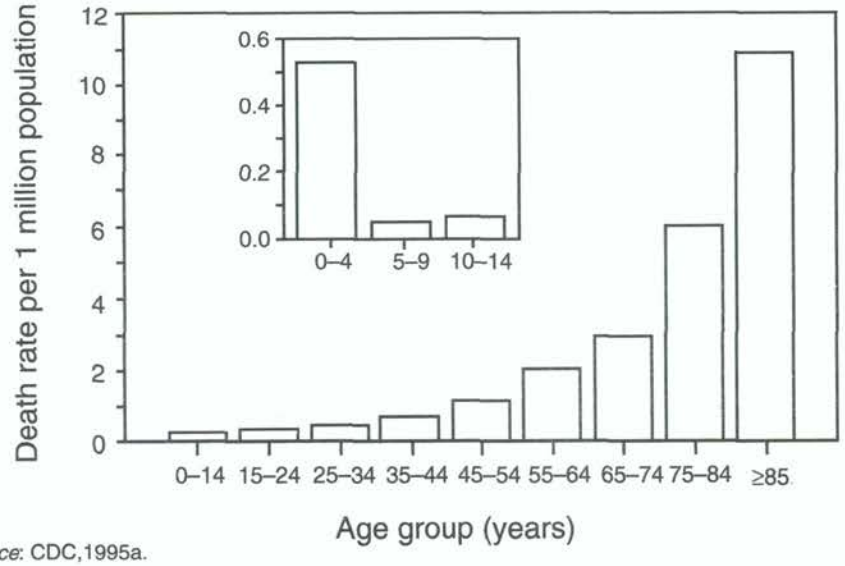
Impacts of stressful weather on physiology and health

Heat stress, physiological adaptation and vulnerability

Extremes of temperature, both hot and cold, can cause physiological disturbance and organ damage, leading to illness or death. One near-certain outcome of climate change is an increase in heat-related morbidity and mortality, particularly in response to episodes of stressful weather, such as heat waves (WHO, 1990b; Kalkstein, 1993). Excessive heat is a well-known cause of heat stress, exacerbated illness and mortality. This was well illustrated by the 1980, 1983 and 1988 heat waves in the USA, during which 1700, 556 and 454 deaths, respectively, were directly attributed to heat (CDC, 1995a). Similarly, in July 1995, a heat wave caused 465 heat-related deaths in Chicago, USA (CDC, 1995b). The elderly, the very young, persons with impaired mobility, and persons suffering from cardiovascular disease, appear to be disproportionally affected by such weather extremes, probably because they have a lesser physiological coping ability (see Fig. 3.1). Socioeconomically deprived segments of urban populations are also relatively more vulnerable to the impact of heat waves, because of poor housing conditions, lack of access to air-conditioning, and greater exposure to the urban "heat island" effect (Kilbourne, 1989).

Some physiological acclimatization to heat-stressful conditions can occur over a period of several days but complete acclimatization to an unfamiliar thermal environment may take several years (Babayev, 1986; Frisancho, 1991). Acclimatization to a perpetually hot climate may entail the activation of a larger percentage of sweat glands than would occur in a moderate climate (Diamond, 1991).

Fig. 3.1. Age-specific mortality for heat-related deaths in the United States between 1979 and 1992: heat-related deaths are defined as deaths attributed to heat exposure due to weather conditions



Source: CDC,1995a.

The health impact of hot weather has been studied predominantly in relation to the most serious health outcome, i.e. death. A major reason for this is that mortality data sets are readily available. Time-series analyses (and other statistical methods) have been used to analyse daily weather characteristics in relation to daily mortality, and applied widely to establish associations between these variables.

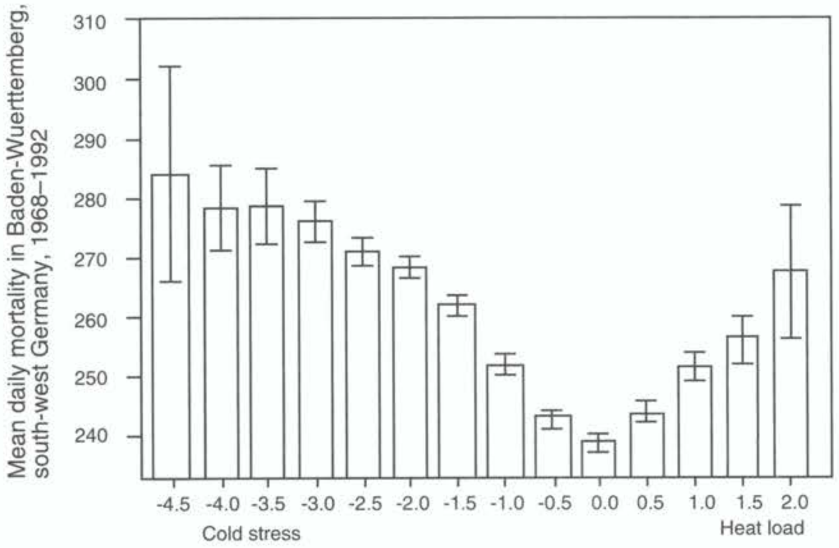
Several studies have shown that heat-related mortality is also affected by such meteorological factors as wind speed and relative humidity. Heat, wind speed and relative humidity together produce an "apparent temperature", that is, the temperature as "perceived" by the human body (Steadman, 1984). Healthy persons possess efficient thermoregulatory mechanisms which cope with increases in apparent temperature. This coping entails heat loss by radiation and convection, and evaporative heat loss by vasodilatation and perspiration (Horowitz & Samueloff, 1987; Diamond, 1991). However, a threshold temperature is evident in most populations studied, indicating that there might be a critical load of heat stress, above which physiological coping mechanisms become inadequate (Kalkstein & Smoyer, 1993). Probably, despite acclimatization, the body cannot cope indefinitely with thermally oppressive conditions. In most temperate climate countries studied, a threshold temperature associated with excess mortality has generally been observable for only 10–15% of the total number of summer days. The threshold temperature for any particular location depends on both the local average temperature and the frequency of extreme temperatures. For example, the threshold temperature for St Louis (southern USA) is 36°C, and 32°C for Detroit (northern USA), but each is exceeded with approximately the same frequency. Thresholds are less apparent in the mortality data of tropical urban areas and of some mid-latitude areas, such as parts of western Europe, that do not experience thermal extremes (Jendritzky, 1996).

The extent of heat-related mortality varies according to geography. Mortality data for many cities in temperate regions, where hot weather is severe but infrequent, show a sharp rise in total mortality during unusually hot weather conditions. In some cases, daily mortality can be more than twice the long-term mortality mean (Longstreth, 1989; Tan, 1994). Conversely, populations in more tropical regions seem to be less affected by temperature extremes. Such differences between regions in the pattern of heat-related mortality may reflect differences in the variability of summer temperatures. In temperate regions, the very hot episodes occur within periods of generally milder weather, and presumably, the physiological "shock value" of a very high temperature is considerable. In tropical cities, the hottest periods usually do not greatly exceed the mean temperature.

Heat-related morbidity and mortality

The onset of heat exhaustion or heat stroke is the most direct impact of heat stress on the human body. But an increase in mortality that is associated with hot weather occurs via a number of mechanisms. For example, deaths from cardiovascular and respiratory disorders, and from some types of accident, typically increase during stressful weather conditions, which explains why heat stroke and heat exhaustion represent only a small proportion of the mortality increase (Larsen, 1990a, 1990b). Because of this diversity of causes of death, the number of *heat*-related deaths is considered to be the number of deaths occurring in excess of the number that would have been expected for that population in the absence of a heat wave.

Fig. 3.2. Relationship between heat load and mortality in south-west Germany using a heat-budget model (95% confidence intervals are also shown)



The scale on the x-axis is a measurement of thermal conditions using a heat-budget model (Klima-Michel Model: Jendritzky et al., 1990). 0.0 indicates optimal conditions for the human subject, i.e. with minimal thermoregulation.

The most recent time-series analyses of meteorological and mortality-related data in cities in Canada, the USA, Greece, Germany, the Netherlands and the Middle East, show that overall mortality rates rise during heat waves (Katsouyanni et al., 1990; Ramlow & Kuller, 1990; Kalkstein & Smoyer, 1993; Kunst, Looman & Mackenbach, 1993; Jendritzky, 1996). Fig. 3.2 shows that daily mortality in south-west Germany increases as heat load increases. In Athens, Greece, the hospital admission rate (and subsequent mortality) increased more than five-fold after the third day of a heat wave in 1987, indicating that duration of heat stress is a critical determinant of thermoregulatory failure (Katsouyanni et al., 1990).

Determining what proportion of observed acute mortality reflects additional loss of life expectancy is difficult. Time-series analyses, by definition, examine the immediate (cross-sectional) correlation between co-fluctuating variables. So even if there is a very strong correlation between daily temperature and daily deaths, the loss of person-time from heat-related deaths cannot be determined by such analyses. (Life-table studies of the effects of stressful climatic events on mortality using study populations exposed and non-exposed to heat mortality risk factors, but otherwise comparable, have not yet been undertaken.) Many of the excess deaths that occur during heat waves occur in persons whose demise, for other reasons, was already imminent. Recent research in the USA suggests that approximately one-third of heat wave-associated deaths occur in persons who would have died within the next several weeks (Kalkstein, 1993). The public health burden of person-time lost may therefore be less than is suggested by the numbers of deaths involved. A related question is whether, as the frequency of heat waves increases, the mortality excess remains constant, or whether successive heat waves produce some form of physiological/behavioural adaptation so that the resultant mortality peaks progressively lessen.

Cold-related morbidity and mortality

In temperate climate countries there is a clearcut seasonal variation in mortality. Much research in temperate climate countries has shown, for instance, that death rates are 10–25% higher in the winter season than those in the summer season (Kilbourne, 1992). Similarly, many studies have shown that in cold and temperate locations, daily cold-related deaths increase as daily wintertime temperature decreases (Khaw, 1995). However, the rate of increase appears to be considerably less steep than that accompanying increasing temperature in summer (Kunst, Looman & Mackenbach, 1993; Touloumi et al., 1994). This relationship is referred to as "J-shaped" to indicate the relatively steeper ascent at high temperatures. Such an asymmetrical relationship may indicate that genetic, physiological and behavioural human adaptation at the lower end of the prevailing global temperature range is superior to that at the higher end. However, the extent of winter-associated mortality that is directly attributable to stressful weather, rather than to seasonal patterns of respiratory infections, is difficult to determine.

The existence of a temperature threshold is less evident in winter than in summer (Kalkstein & Davis, 1989; Kunst, Looman & Mackenbach, 1993). In fact, Jendritzky (1996) found no cold-temperature threshold in Germany, observing instead that mortality increased in uninterrupted linear fashion as cold stress increased (Fig. 3.2). However, in other regions with mild climates, such as the Netherlands and Brisbane, Australia, mortality rates rise linearly with decreasing wintertime temperature (Keatinge, Coleshaw & Holmes, 1989; Frost & Auliciems, 1993; Kunst, Looman & Mackenbach, 1993). Elsewhere though, for instance in Montreal, Canada, and Minneapolis, USA, which are subject to colder weather, the increase in mortality that accompanies decreasing winter temperatures, is only slight (Kalkstein, 1988; Frost & Auliciems, 1993). Possibly, behavioural responses such as cold avoidance are an important thermoregulatory process at very low temperatures in populations well-accustomed to extreme cold.

Some evidence exists that, in extreme climates, stormy rather than very cold weather is responsible for some wintertime excess mortality (Rogot & Padgett, 1976; Glass & Zack, 1979). In the USA, heart attack related to overexertion may be a major cause of wintertime death (see, for example, Faiche & Rose, 1979). The increased risk of mortality in persons with cardiovascular disease in winter may simply reflect a cold-induced tendency for blood to clot, perhaps exacerbated by the effect of wintertime respiratory infections (Keatinge, Coleshaw & Holmes, 1989; Woodhouse et al., 1994).

The number of deaths from influenza, pneumonia and accidents also increases during winter (Richards & Marriott, 1974; Curwen, 1990; Frost & Auliciems, 1993). As respiratory infections depend upon aerosol transmission, usually in confined poorly-ventilated places, a small rise in winter temperatures should reduce this risk since people usually spend less time indoors during warmer weather. The postulated importance of infectious disease transmission in relation to winter mortality is supported by the observation that the average lag-time between stressful weather and subsequent mortality is longer in winter than in summer (Kalkstein, 1988; Larsen, 1990a; Kunst, Looman & Mackenbach, 1993). However, annual influenza outbreaks do not appear to correlate with mean winter or monthly temperatures (CDC, 1994a; Langford & Bentham, 1995). Admittedly, though, the interannual variability in the virulence of influenza strains makes interpretation of the relevant data difficult. The relationship between winter temperatures and respiratory mortality therefore remains uncertain.

Potential impact of climate change on mortality

If weather variability remains unchanged, climate change would necessarily be accompanied by an increase in the number of days that exceed threshold high temperatures (see also Chapter 2). Data from the 1980s in Missouri, USA, show that considerably more very hot days were experienced in years during which mean summer temperatures were 2–3°C higher than average (CDC, 1989). It has been estimated that by 2050, climate change could increase severalfold the frequency of extremely hot days in Washington DC, USA, and the occurrence of extraordinarily hot summers in England (CCIRG, 1991).

The evidence of a J-shaped temperature stress–mortality relationship, which comes mostly from developed countries, suggests that decreases in winter mortality accompanying climate change would partly offset the anticipated summertime increases in mortality (Rango, 1984; Tan, 1994). The net effect on mortality would of course depend on the frequency of morbidity associated with cold-sensitive, seasonal diseases. A recent British study has forecast that wintertime temperature increases of 2–2.5°C, as predicted under typical climate change scenarios, would result in 9000 fewer winter-related deaths annually by the year 2050 in England and Wales (Langford & Bentham, 1995). Under this scenario, just over half of these "avoided deaths" would have been from ischaemic heart disease and stroke, and 5–10% each from chronic bronchitis and pneumonia. But the sensitivity of total mortality rates to increases in temperature during hot summer episodes is nevertheless likely to be greater than their sensitivity to a marginal warming in winter. However, given that most of the published research refers to the experience of developed, non-tropical countries, this conclusion must be treated cautiously.

Although much is known about the immediate effects upon health of short-term exposures to extreme temperatures, the longer-term effects of climate *per se* remain poorly understood. A conditioning effect of climate on susceptibility to disease, or vulnerability to sudden exposures to climate extremes has often been postulated, but not subjected to quantitative study. Predicting the degree of change in longer-term climate effects on human health by extrapolation from empirical knowledge is therefore not yet possible. Yet since populations are able to adapt both physiologically and culturally to changes in their environment, changes in background climate may not interfere significantly with human response mechanisms to other health stresses. Wider-ranging research, with better quantification of health effects, is obviously needed.

Climate change, thermal stress and mortality: a four-country study

Recent interest in forecasting the impact of climate change upon patterns of death and illness has prompted new research on climate and health, particularly in relation to the impacts of heat waves. A prominent example of this type of research is the project on heat-related mortality excesses of the Climate Change Division of the US Environmental Protection Agency (USEPA) (Kalkstein & Tan, 1995; Scheraga & Sussman, in press). This project is summarized in the following section, both as a source of new information and to illustrate the type of mathematical modelling techniques now being used in climate–health research.

Methods and country results

Urban populations in Canada, China, Egypt and the USA were chosen for study. Detailed historical mortality databases were available for all four countries. For the USA, detailed data on weather and age-specific and cause-specific mortality were evaluated for an 11-year period within the period 1964–1980, for 15 cities with different climates. Environment Canada provided daily mortality data for ten Canadian cities for the period 1958–1988. These data were grouped by age and cause of death into a weather-related group that included all respiratory, cardiovascular, influenza, injury and heat stroke/heat-stress deaths, and a total death group. For China, daily summer and winter mortality data relating to persons aged over 65 years were obtained for the period 1980–1989 for Shanghai, which has a mid-latitude climate, and Guangzhou, which has a subtropical climate. Specific causes of death were not available. For Egypt, mortality data were obtained for Cairo for the period 1981–1985, and daily numbers of deaths were tabulated, although cause and age of death were not available.

Two steps were followed to ascertain the historical relationship between weather and mortality. Firstly, the threshold temperatures were determined objectively for each urban population, by analysing temperature–mortality relationships (Kalkstein & Davis, 1989). For example, the summer threshold temperature in Shanghai is 34°C; mortality increases markedly at temperatures above this level. Secondly, a synoptic approach to weather variables was used to identify specific air masses associated with particular levels of mortality (Kalkstein, 1991a). This procedure yielded a set of meteorologically-defined air masses — such as "continental polar" and "maritime tropical" — for each city, which were then correlated with health outcomes (see Box 3.3.). In Shanghai, for example, days with high afternoon temperatures, low wind speeds and low humidity were associated with the greatest mortality increases. Each day, with its recorded meteorological characteristics, was thus allocated to a particular synoptic category (Kalkstein, 1991a).

A regression analysis incorporating eight selected weather variables (see Table 3.4) was then applied to determine which synoptic category accounted best for the variation in mortality associated with temperatures that exceeded the threshold (Box & Wetz, 1973). Potential lag-times of up to three days were allowed for. The regression analysis also took account of where each above-threshold day fell within the overall sequence of days, and whether the day occurred early or late in summer. This enabled both short-term and seasonal acclimatization to be evaluated.

Table 3.4. Weather variables used in four-country study to identify synoptic weather categories (air masses)

Maximum temperature
Minimum temperature
Maximum dewpoint temperature
Minimum dewpoint temperature
Cloud cover[a]
Wind speed[a]
Time of season[b]
Day in sequence

[a] Values represent cloud cover and wind speed measured at 2.00 pm local standard time.
[b] Determines whether an above threshold day occurs early or late in the season and evaluates short-term and intraseasonal acclimatization.

The most discriminating algorithms (models) were then used to estimate future mortality attributable to hot weather, based on estimated temperature data for the years 2020 and 2050, derived from two transient climate change experiments (GFDL89 and UKTR) (IPCC, 1994b).

Acclimatization of the population must also be considered when assessing the impact of climate change on future mortality. To ignore acclimatization is to assume that people in each locale would be affected in the future by sporadic high temperature episodes in the same way as they are today, even though with climate change these episodes would occur more frequently. Yet their coping mechanisms might adjust and become similar to those of people who presently live in hotter climates, and who are acclimatized to greater heat levels. Thus if climate change-related increases of several degrees in mean temperature occur gradually, over several decades, the number of heat-related deaths may in fact remain stable.

A procedure was therefore developed to estimate such future acclimatization (Kalkstein, 1991b). Mortality that had occurred during heat waves during cool summers was compared with mortality that had occurred during heat waves during hot summers. It was reasoned that if people acclimatize seasonally, greater heat wave-related mortality increases would occur in cooler summers, when heat waves are infrequent, than in hotter summers when heat waves are common. Populations able to acclimatize during the span of one summer, and this has been observed, might also be expected to acclimatize to a slow, long-term warming. Recent research on the role of heat shock proteins, synthesized by many organisms in response to temperature stresses, suggests that these proteins may assist rapid acclimatization (Born et al., 1990; Elliot, 1992).

Such acclimatization estimates take into account physiological and short-term behavioural adjustments only. They do not consider potential infrastructure changes such as architectural improvements to buildings or more widespread use of air-conditioning. Indeed, predicting exactly how urban and social structures might change under climate change conditions is impossible. Nevertheless, the procedure outlined here should yield realistic estimates of acclimatization for the next several decades since cultural or social adjustments will probably lag far behind physiological adjustments, especially in developing countries (Kalkstein, 1991b). That said, there is much that we do not yet know about the extent, time-course and consequences of acclimatization. The following research results, which incorporate acclimatization adjustments, are therefore illustrative, not definitive.

USA

Estimates of present-day heat-related deaths were made for the 15 US cities, using the methods described above. Those cities in northern and mid-western USA, where high temperatures occur irregularly, showed the largest excess in the rate of heat-related deaths in summer. For those cities in the southern USA, where heat is relatively constant, the attributed excess rates were smaller. Furthermore, very hot weather early in summer was found to have a greater impact than very hot weather in August. These findings are consistent with the concept of acclimatization.

The mathematical relationships, which were derived historically, were then used to forecast future trends in mortality for doubled-carbon dioxide (CO_2) climate scenarios. The calculations assume that the sizes and age structures of the populations remain constant, and predict that if acclimatization to warmer weather does not occur, then the number of heat-related deaths might increase several-fold over present levels by the year 2050 (Table 3.5). Most of these additional

Table 3.5. Total summer heat-related deaths[a] in selected cities: current mortality and estimates of future mortality under two different climate change scenarios

City	Present mortality[b]	GFDL89 climate change scenario				UKTR climate change scenario			
		Year 2020		Year 2050		Year 2020		Year 2050	
		no acc	acc	no acc	acc	no acc	acc	no acc	acc
United States									
Atlanta	78	191	96	293	147	247	124	436	218
Dallas	19	35	28	782	618	1364	1077	1360	1074
Detroit	118	264	131	419	209	923	460	1099	547
Los Angeles	84	205	102	350	174	571	284	728	363
New York	320	356	190	879	494	1098	683	1754	971
Philadelphia	145	190	142	474	354	586	437	884	659
San Francisco	27	49	40	104	85	57	47	76	62
Canada									
Montreal	69	121	61	245	124	460	233	725	368
Toronto	19	36	0	86	1	289	3	563	7
China									
Shanghai	418	1104	833	2950	1033	1308	1046	1486	1089
Egypt									
Cairo	281	476	N/A	830	N/A	839	N/A	1024	N/A

no acc = no acclimatization; acc = acclimatized populations; N/A = not applicable

[a] Numbers represent average summer-season heat-related deaths for each city under each climate change scenario. For example, during a typical summer today, 78 extra deaths occur in Atlanta from heat-related causes and, assuming no acclimatization, this number rises to 191 deaths. Numbers assume no change in population size and age distribution.

[b] Raw mortality data

Source: Kalkstein et al., in press b.

deaths would be in the larger cities studied such as Los Angeles, New York and Philadelphia, since the populations of these cities are larger. The results which take acclimatization into account show more modest projected increases.

The projections in Table 3.5 include several unexpectedly high and several unexpectedly low figures. This reflects the limitations of this type of modelling exercise; it is the pattern, rather than any specific figure, that is most informative.

Canada

The relationship between summer weather and mortality in Canada appears to be less strong than in the USA. Summertime threshold temperatures were evident for only two of the ten cities studied: 29°C for Montreal and 33°C for Toronto. (Both are considerably lower than the summertime threshold temperatures of most US cities). These two Canadian cities may thus represent the northern limit of the distribution of the heat-related mortality pattern evident in North America. This accords with the observation that air masses from tropical sources do intrude occasionally into southern Canada.

The synoptic approach revealed significant summer heat–mortality relationships for three cities: Toronto, Montreal and Ottawa. The absence of such a relationship for the other cities might, since their populations are smaller, reflect relatively greater distortions of mortality peaks, due to non-weather causes such as major traffic accidents (see, for example, Kalkstein & Davis, 1989). Analysis of present-day mortality for these three cities indicates that several hundred extra deaths can be attributed to stressful hot weather during typical summers (see Montreal and Toronto in Table 3.5 also). This approximate figure resembles that calculated for moderately sensitive US cities, such as Los Angeles and Minneapolis (Longstreth, 1989). Predictive modelling (with population size and age structure held constant) indicates that climate change could increase heat-related mortality significantly if populations do not acclimatize. If acclimatization does occur, very little excess heat-related mortality would be expected in Toronto, although the values predicted for Montreal still amount to an excess of several hundred deaths per summer.

China

The study showed that future warming may affect mortality in China markedly, especially in mid-latitude cities such as Shanghai. Similar threshold temperatures were apparent for Shanghai and Guangzhou. However, in Shanghai, the rise in mortality at temperatures exceeding the relevant threshold temperature was much steeper than in Guangzhou (Fig. 3.3). (This finding accords with the geographical pattern found for US cities.) The historical mortality data showed that, during an average summer, the rate of heat-related deaths is approximately 50% higher in Shanghai than in Guangzhou. The lesser increase in heat-related mortality estimated for Guangzhou reflects the small degree of climatic variability experienced by this city in summer.

Box 3.3. Identifying stressful weather categories in Shanghai and Guangzhou

Weather and mortality data for two cities in China were evaluated to identify stressful weather categories or "air masses". Two synoptic categories of potentially stressful air masses were identified in Shanghai, whereas no particular air mass appeared to be associated with significantly increased mortality in Guangzhou. In Shanghai, Air Mass No. 1, characterized by hot, clear and dry conditions, was associated with a mean daily mortality about 9% above the total mean. However, although this air mass occurs on only 14% of summer days, it was present for over one-third of the duration of the 50 highest mortality days recorded in Shanghai during the sample period. Air Mass No. 2 in Shanghai, associated with humid maritime tropical conditions, appeared to be even more stressful. This air mass was present for 60% of the duration of the top 50 mortality days, which is remarkably high considering that its normal summer frequency is less than 18% during an average summer in Shanghai. Thus the combination of these two apparently stressful air masses — which occur for less than 33% of the time during summer — account for 47 (or 94%) of the top 50 mortality days in Shanghai. It is projected that these air masses would occur much more frequently with climate change. Using a doubled-CO_2 climate change scenario (from a GISS climate model) it is estimated that Air Mass No. 2 would almost double in frequency, from 18% to 33%. Thus climate change would be expected to increase heat-related mortality in Shanghai.

Analyses of historical data indicate that acclimatization will not be substantial in either Shanghai or Guangzhou. Under the climate change scenarios used here, Shanghai's summer climate will become warmer, but its degree of variability will not change. In other words, intense sporadic heat waves would continue to occur in Shanghai, rendering population acclimatization less likely.

Fig. 3.3. Relationship between maximum temperature and mortality in Shanghai and Guangzhou, China

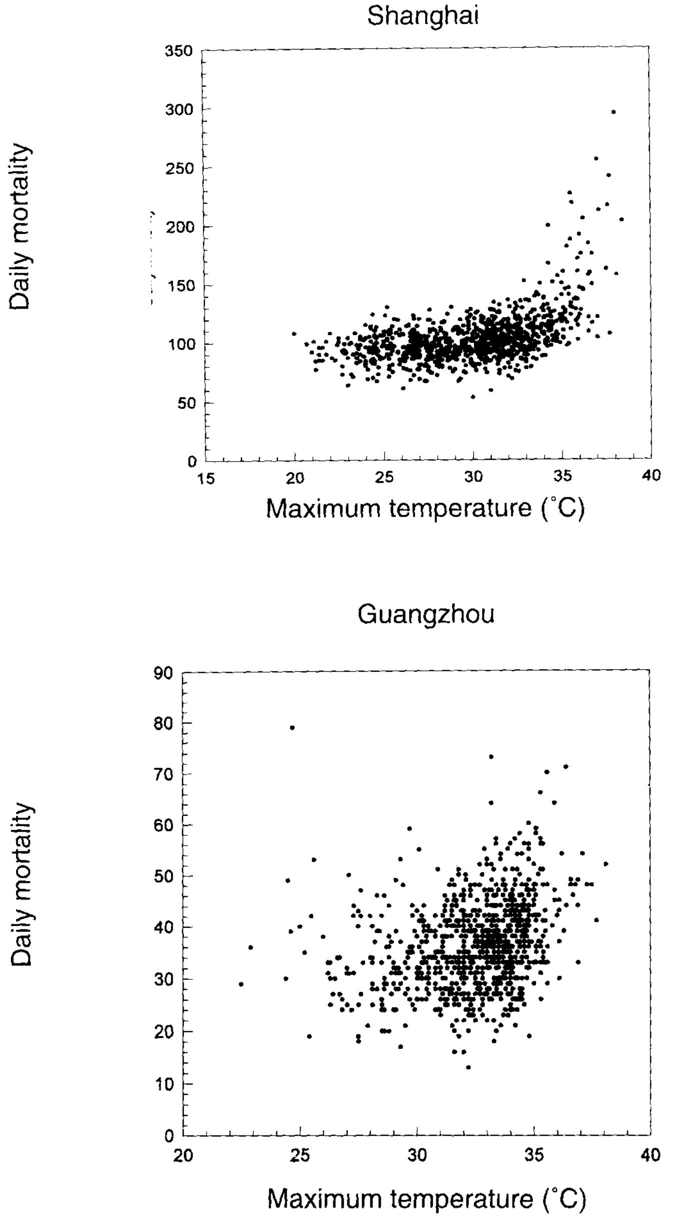
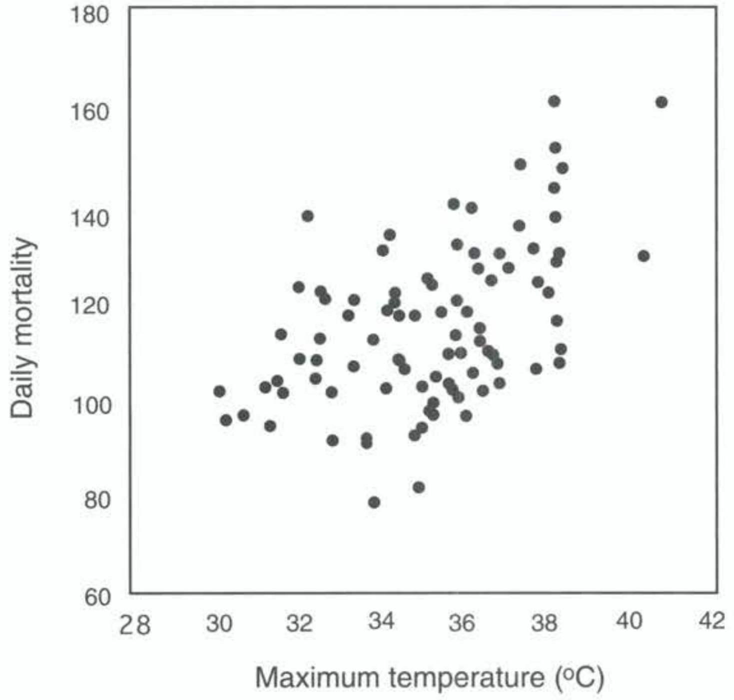


Fig. 3.4. Relationship between maximum temperature and mortality in Cairo, Egypt, 1984



Egypt

Weather variables other than temperature were unavailable for Cairo. The data for Cairo for the period 1981–1985 indicate that total mortality increases as temperature increases (Fig. 3.4). Nevertheless, no threshold temperature is evident for Cairo.

In Cairo, the timing of very hot weather during the hot season has little impact; a very hot day in August affects mortality as strongly as in June. (In most other locales, heat has a much greater impact if it occurs early in the season.) Neither do consecutive hot days appear to amplify heat-related mortality. This also differs from Chinese, Canadian, and US results, which indicated that the impact of heat increases with increasing duration of heat. In Cairo, the impact of hot weather episodes on heat-related mortality remains fairly constant irrespective of whether the summer in question is hot or cool, implying that seasonal acclimatization does not occur.

Comparisons with major cities in the USA, Canada and China suggest that Cairo is comparatively sensitive to episodes of very hot weather. However, if the existing low variation in day-to-day maximum temperatures persists into the future, despite climate change, this may preclude increases in heat-related mortality. This would not be the case though if rising temperatures place more of Cairo's summer weather outside the range of human tolerance. Present-day heat-related deaths for Cairo are estimated to reach almost 300 during an average summer (Table 3.5).

Factors influencing vulnerability to stressful weather

Socioeconomic factors

Socioeconomic disadvantage has an adverse influence on health. However, direct indices of socioeconomic status are not recorded routinely on medical records and death certificates. Therefore, in a recent study of heat-related mortality in four US cities (Atlanta, New Orleans, New York, and St Louis), information on ethnicity was used to identify residential segments of the population who were likely to be in a low-income bracket (Smoyer, 1993). The study found that black residents were generally more prone to heat-related mortality than other population groups. This was most evident in New Orleans and St Louis, particularly among the elderly. In New York City, however, the inner urban heat island effect upon mortality was stronger than that of socioeconomic circumstance.

Another study examined the relationship between mean seasonal heat-related mortality, for the period 1964–1980, and the socioeconomic characteristics of the populations of 15 US cities (Chestnut et al., 1995). Cities with a large proportion of workers in manufacturing experienced higher rates of heat-related death. Furthermore, cities with high inner urban densities, a high proportion of homes with poor sanitation, and populations with low profiles of educational attainment, were found to be more susceptible to heat-related mortality.

Box 3.4. Air-conditioning and mortality

During recent decades, access to air-conditioning has increased considerably in the USA. For example, in St Louis the percentage of homes with air-conditioning increased from 40% in 1965 to 91% in 1992. Overall mortality rates declined during the same period, particularly for heat-stress episodes. As the use of an artificially cooled environment, even for a few hours each day, reduces the risk of heat-related illness, it is tempting to attribute the decline in heat-stress mortality to increased access to air-conditioning.

Changes in mean summer mortality over successive years were studied at the population level in eight US cities: Birmingham, Chicago, Memphis, New Orleans, New York, Philadelphia, Phoenix and St Louis. But determining whether a decrease in disease or mortality is due to one particular factor, such as temperature, is not easy. This is because other relevant factors that affect mortality, such as air pollution levels, could also have been changing over time. In this particular study, the data were standardized for inter-annual trends in population size, age structure and health care coverage. But since data on access to air-conditioning at the individual level, for use in a case–control study, are lacking, the association remains unresolved. A case–control study of heat-stress mortality risk factors, undertaken in several locales and using a standard protocol, could clarify the preventive value of air-conditioning and other means of reducing heat stress, such as cold baths and electric fans. Such a study could also reveal the potential value of health warning approaches to reducing heat stress risk factors, such as dehydration and loss of salts, in the elderly.

Sources: Kilbourne, 1992; Stern, Neal & Smith, 1993; Kalkstein et al., in press b; Scheraga & Sussman, in press.

Intraseasonal variation in heat-related mortality

Two considerations complicate interpretation of the mortality impact of heat waves. Firstly, many of the deaths may be of persons who would have died very soon anyway. Secondly, the mortality impact of successive heat waves within a single season is likely to be subject to the effects of progressive selection and adaptation.

Fig. 3.5 shows that total mortality during and immediately after a New York heat wave in 1966 was well above the long-term mean (Kalkstein, 1993). On one particular day, the mortality rate was almost three times this value. However, during the period following the heat wave, daily mortality appeared to be below the long-term mean, presumably because of short-term mortality displacement. During the heat wave, a total of 19.8 deaths per 100 000 was accumulated above the long-term mean. For the post-heat wave period, in which mortality was significantly lower than the long-term mean, a total of 8.6 deaths per 100 000 was accumulated below the long-term mean. Assuming that no selection bias existed (for example, because people moved away from the heat), this indicates that 43% (i.e. 8.6/19.8 x 100%) of the total extra deaths during the heat wave were due to short-term displacement (Table 3.6).

Some degree of mortality displacement was found for all the heat episodes evaluated in the four-country study (Scheraga & Sussman, in press). The values for each city over separate episodes were fairly consistent, but significant differences between cities were observed. Overall, it appears that a proportion of the excess mortality occurring during a heat episode would otherwise have occurred shortly afterwards. Even so, in most instances the majority of deaths occurring during heat waves are "extra" deaths, occurring in persons who would otherwise not have died shortly afterwards.

Fig. 3.5. Daily summer mortality during a New York heat wave in 1966

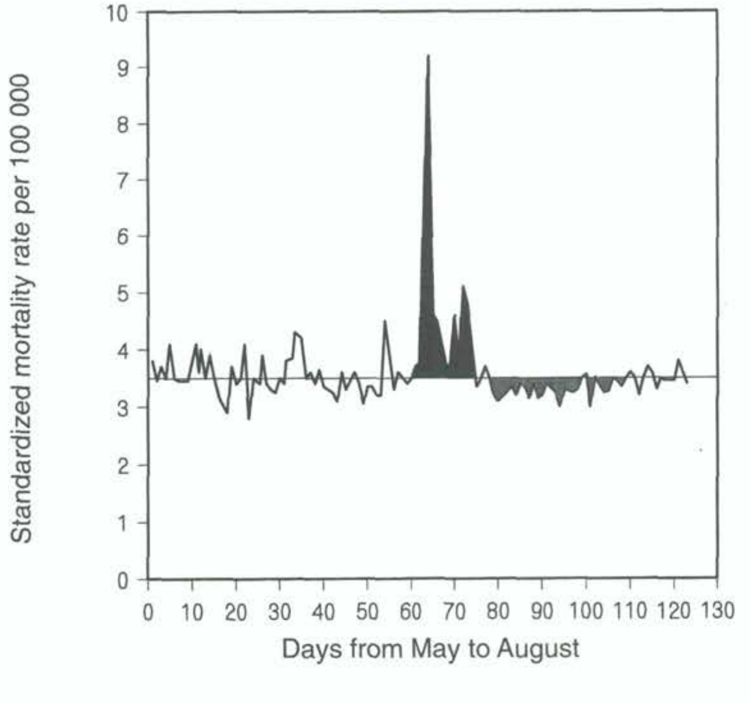


Table 3.6. Short-term mortality displacement assessment based on mortality during six heat waves in three US cities

City and year	Mean standardized daily summer mortality (per 100 000)	A: Sum of mortality during heat wave (sum above mean)[a]	B: Sum of mortality after heat wave during period when mortality was significantly lower than in preheat event (sum below mean)[b]	Percentage of total extra deaths during heat wave due to short-term displacement [B/A x 100%]
New York 1966	3.50	19.8	8.6	43%
New York 1975	3.02	8.7	3.6	40%
New York 1984	2.67	7.8	3.0	39%
St Louis 1966	2.90	33.4	7.3	22%
St Louis 1980	2.82	17.1	2.7	16%
Birmingham 1980	2.44	14.2	10.2	72%

[a] See black area in Fig. 3.5
[b] See grey area in Fig. 3.5

Links between air pollution, climate and human health

Combined exposures

For the next fifty years, fossil and biomass fuels will almost certainly continue to be the world's principal sources of energy (Johansson et al., 1993). Combustion of these fuels is a major source of CO_2 and the major primary air pollutants (carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbons and particulates). It is well established that exposure to these air pollutants can have a range of serious health effects, especially if severe pollution episodes occur (WHO, 1994a).

Although the production of air pollutants is predominantly an accompaniment to climate change, and not a direct consequence of it, there are some important close relationships between the two. The main links between the climate system, air pollution, ecosystems and human health are outlined in Box 3.5.

Urban air pollution concentrations have been much reduced in developed countries in recent decades (World Bank, 1992). For instance, decreased industrial and domestic use of coal, and the installation of stack scrubbers in industrial facilities, has resulted in considerably lower wintertime exposures to SO_2 and smoke. However, increases in vehicular exhaust emissions have increased ambient air concentrations of NO_x, CO, particulates (especially from diesel engines) and photochemical oxidants.

Household fuel use in developing countries is another source of greenhouse gas (GHG) emissions and local air pollution (see also Box 3.6). The resulting indoor and outdoor air pollution exposure is a major public health problem, particularly in colder areas, such as the Himalayas, the highlands of Papua New Guinea, and in parts of China, where it is a cause of respiratory disease, including lung cancer (Pandey et al., 1989; Romieu et al., 1990).

Box 3.5. The climate system, air pollution, ecosystems and human health

The main links between the climate system, air pollution, ecosystems and human health are outlined below.

- In urban environments, the formation of secondary air pollutants (from primary pollutants) is enhanced at higher temperatures. Climate change would accelerate the atmospheric chemical reactions that produce the secondary air pollutants known as photochemical oxidants and which include ozone.
- Synergistic biological interactions appear to operate whereby the health impact of the combined exposure to stressful weather and air pollution exceeds the simple summation of their separate effects.
- Sulfates and particulates (two of the major pollutants produced by coal combustion) in the lower atmosphere alter the lower atmosphere's radiative balance by reflecting sunlight and acting as cloud condensation nuclei, thus diminishing the greenhouse effect in local areas.
- The burning of fossil fuels leads to "acid rain" which damages terrestrial ecosystems, which in turn affects human populations negatively. For example:
  — Various metals in soil that become mobilized by acidification (such as aluminium and heavy metals) can be absorbed by edible plants and enter aquatic ecosystems. Acidification also leaches calcium from soils and lowers its levels in plants.
  — Acid rain damages freshwater ecosystems and kills fish, thereby relieving mortality pressure on mosquito larvae.
  — In marine systems, acid rain enhances eutrophication, thus contributing to the growth of hazardous algal blooms.
- Microorganisms — such as spores and pollen — are a form of air pollution. Warmer weather increases spore release and pollen dispersal. Inhalation of windborne spores causes fungal infections. For example, coccidioidomycosis is a pulmonary fungal infection in humans and animals. An epidemic of coccidioidomycosis in south-west USA was attributed to protracted drought followed by heavy rains, which were conducive to the growth and airborne spread of *Coccidioides immitis* spores.

Sources: Seinfeld, 1986; Epstein, Ford & Colwell, 1993; CDC, 1994c; IPCC, 1994b; Pappagianus, 1994; Mitchell et al., 1995.

Physicochemical interactions in the atmosphere

Physicochemical interactions influence the production of photochemical oxidants. In particular, increases in temperature or ultraviolet radiation (UVR) in the lower atmosphere enhance the chemical reactions that produce photochemical oxidants such as tropospheric ozone (O_3) (Akimoto, Nakane & Matsumoto, 1993; Chameides et al., 1994). (See Chapter 2 for discussion of stratospheric ozone.) Therefore, if climate change causes the lower atmosphere to warm, those chemical reactions would tend to accelerate and concentrations of photochemical oxidants would increase. De Leeuw and Leyssius (1991) have estimated that the increased UV flux in the lower atmosphere resulting from a 10% depletion in stratospheric ozone, combined with a 10% increase in surface temperature (around 1.6°C), would cause an approximate 3% increase in the rate of production of tropospheric ozone.

Ozone is a highly reactive gas which can oxidize molecules directly, and create high-energy free radicals that damage cell membranes. It has various acute effects upon the respiratory tract, impairing lung functioning and damaging cells (Romieu, 1992). In asthmatic children exposed to low O_3 concentrations, subsequent exposure to SO_2 impairs lung functioning at concentrations that would otherwise have no effect (Koenig et al., 1990). Studies with laboratory animals have demonstrated some of the biological effects of O_3: these include increased permeability of alveolar epithelium, impaired pulmonary defence against viral and bacterial infections, and diminished lung function (Mustafa et al., 1984; Jakab, 1987; Gilmour et al., 1991; Young & Bhalla, 1992). These acute respiratory effects have been observed particularly in relation to childhood asthma. However, little evidence has been found that O_3 affects mortality (Schwartz, 1994).

In addition to the enhanced formation of photochemical oxidants, climate change may also affect the dispersion of primary air pollutants through its impact on the convective (circulatory) motion of the atmosphere. This convective motion determines increases and decreases in air pollutant concentrations, temperature and relative humidity (Lumley & Panofsky, 1964). When air movement is slow or stagnant in the bottom layers of the lower atmosphere, exposures to air pollutants and higher temperatures are greater and more prolonged. Poorer atmospheric dispersion would, for example, lead to increased urban concentrations of air pollution generated by motor vehicles. Changes in prevailing wind patterns could also affect the impacts of local air pollution by changing pollution dispersal patterns.

Normally, air temperature decreases with increasing height or altitude. This is referred to as the "lapse rate" of atmospheric temperature. Air pollutants and heat are dispersed more rapidly at a lapse rate of -1°C/100 m than, for example, at a lapse rate of -0.5°C/100 m. Moreover, pollutants and heat are dispersed rapidly when atmospheric conditions are turbulent and unstable — for example, on a windy day with high clouds (Pasquill, 1962; Monin, 1970). In locations where temperature does not decrease with altitude, air motion is stagnant and very stable, and air pollutants tend to remain close to their sources (Turner, 1970). If temperature increases with altitude, a "temperature inversion" occurs. In such instances, pollutants are dispersed slowly and ground-level air pollution concentrations increase. Additionally, because heat is retained, the ground-level temperature increases. Temperature inversions also occur when a stagnant high pressure system is present in the upper portions of the troposphere. Climate warming may exacerbate the pollution levels of air masses trapped in this way.

Health effects of weather and air pollution

Many studies have shown that stressful weather and high levels of air pollution have independent adverse health effects. But most of these studies have focused primarily on the independent effects of one of these two environmental stresses (usually air pollution); fewer studies have successfully separated and quantified both weather-induced and pollution-induced mortality. Moreover, the synergistic impacts of weather and pollution on morbidity and mortality, especially acute mortality, are not yet well understood.

Box 3.6. Household fuel use in developing countries

Industrial processes and transportation are the primary sources of greenhouse gases (GHGs). However, small diffuse sources of GHGs also contribute to the greenhouse effect. Thus household biomass combustion is estimated to account for as much as one-fifth of all atmospheric carbon released through fuel use. Household biomass cooking stoves are estimated to account for 2–4% of total net anthropogenic GHG emissions.

In developing countries, indoor concentrations of particulates, carbon monoxide (CO) and hydrocarbons due to biomass combustion are typically found to exceed health-based standards. Since about half of the world's population cooks and/or heats with simple solid-fuel stoves — often with poor ventilation — resulting in high indoor pollutant concentrations, the total potentially exposed population is large.

Indoor air pollution can affect health significantly. Pulmonary disease and cardiopulmonary mortality has been linked to atmospheric particulates at concentrations 100 times lower than are typically found in biomass-burning households. The largest studies on indoor air pollution have focused on acute respiratory infections (ARI) in children and lung cancer in adults. ARI, principally in the form of pneumonia, is the leading killer of young children worldwide, causing some 4.3 million deaths annually. This is one-third more than the next category (diarrhoea). Studies indicate that the risk of ARI is two to five times higher for young children exposed to unvented biomass smoke than for children in households that use modern fuels such as kerosene or gas. Due to widespread potential exposures, a significant portion of ARI mortality might be attributable to indoor air pollution.

In developing countries, gross lung cancer rates are rising, due primarily to a combination of extended life expectancy and smoking. However, compared to men, lung cancer in women is much less correlated to smoking; women are far more exposed to emissions from household fuels and this may be responsible for their disease outcome. For example, in China, women consistently burning coal for cooking are at a two- to nine-fold greater risk of developing lung cancer compared to those using gas stoves. These findings are of particular concern because many developing nations are beginning to switch to coal as a preferred household fuel.

Individual households using biomass fuels can take measures to reduce GHGs and improve their family's health by shifting to more efficient fuels such as kerosene or gas, and switching to stoves with higher combustion efficiency. Gaseous products of incomplete combustion, such as methane, have a greater greenhouse warming potential than does carbon dioxide. Particulates, CO, and hydrocarbons are also products of incomplete combustion that are very detrimental to health. Reducing these combustion products by introducing more efficient fuels and stoves in developing countries could, therefore, improve human health while reducing anthropogenic contributions to global warming at the same time.

Sources: Ahuja, Joshi & Smith, 1987; Dockery et al., 1989; Schwartz, 1989; Chen et al., 1990; Smith et al., 1993; Smith & Liu, 1994.

Some studies differentiating between the impacts of air pollutants and weather upon mortality have been reported from the USA and Europe (see, for example, Shumway, Azari & Pawitan, 1988; Schwartz & Dockery, 1992; Pope et al., 1995, with reference to the USA, and Katsouyanni, Pantazopoulu & Touloumi, 1993; Kunst, Looman & Mackenbach, 1993; Touloumi et al., 1994; Pope & Kalkstein, 1996, with reference to Europe). These studies have generally found significant associations between suspended particulates and mortality, while time-series analyses have demonstrated that the acute effect of air pollutants (particularly fine particulates, often referred to as PM_{10}) on mortality exceeds that of temperature. Recent studies of daily mortality patterns in London, UK, have shown the significant health impact of exposures to acid aerosols and particulates. Weather variables appeared to play a lesser role (Ito et al., 1993), confirming results previously obtained for London (see, for example, Thurston et al., 1989). (London's marine climate, with its infrequent thermal extremes, is rather benign compared to many large American cities.) However, other studies have found that pollution has little impact on short-term variations in mortality relative to the impact of weather (see, for example, Biersteker & Evendijk, 1976; Ramlow & Kuller, 1990). Indeed, when a synoptic climatological approach is used, weather is implicated as the primary environmental factor influencing acute mortality associated with short exposures to stressful climatic conditions (Kalkstein, 1991a; 1993; Kalkstein & Tan, 1995).

An important, but little researched topic, is the biological interaction between the health impacts of weather variables and air pollution. Several investigators have examined this issue (including Shumway, Azari & Pawitan, 1988; Shumway & Azari, 1992; Katsouyanni, Pantazopoulu & Touloumi, 1993). Shumway, Azari & Pawitan (1988) examined the synergistic relationships between weather and pollution on mortality in Los Angeles, USA, and concluded that significant interactions may occur, especially when low or high temperatures combine with high pollution levels. Likewise, a recent mortality study in Philadelphia, USA, revealed an apparent synergistic relationship between hot weather and particulates exposure (Wyzga & Lipfert, in press). However, two studies in the Netherlands, in settings of relatively low air pollution, found that temperature extremes in summer and winter were the primary determinants of mortality risk, and little influenced by variation in pollutant levels (Kunst, Looman & Mackenbach, 1993; Mackenbach, Looman & Kunst, 1993).

It is important to note that most studies of air pollution, climate and health have focused on *acute* rather than *long-term* effects. However, the biological processes underlying these two categories of outcome differ, at least in part (McMichael, 1996). For example, many of the acute deaths resulting from air pollution episodes (or from heat waves, as discussed above) occur in highly susceptible individuals, many of whom are already sick or frail. The effect is thus a "last-straw" triggering of some kind: for instance, causing a blood-clot to form in an already occluded coronary artery. But long-term exposure to serious air pollution may cause previously healthy persons to gradually develop a chronic disease that significantly impairs and shortens their lives. Such chronic effects may actually result in greater reductions in life expectancy than those due to excesses of mortality associated with acute episodes — and are therefore more serious in public health terms. Unfortunately, studying the health impacts of long-term air pollution exposure is much more difficult than carrying out time-series analyses of the effects of high-pollution episodes on daily mortality levels. Hence, there is an imbalance in the available evidence, and additional research is required.

Weather-related impacts on the respiratory tract

Respiratory disorders are typically caused by allergic reaction, infection, or inhalation of dusts or chemicals, and may be influenced by weather and climate, either directly (for instance, via sudden drops in temperature) or indirectly (for instance, via an increase in pollutant levels).

The production of plant aeroallergens is very sensitive to climate (Emberlin, 1994). Climate change could therefore be anticipated to affect the pattern of various seasonal allergic disorders (especially hay fever and asthma) via its impact on the production of such allergens. Altered pollen production would principally reflect shifts in the natural and agriculturally-managed distribution of many plant species, including birch trees, grasses, ragweeds, and various crops such as oil-seed rape and sunflowers.

Hay fever (allergic rhinitis) increases seasonally, in association with pollen release. The causation, exacerbation and seasonal distribution of asthma is more complex. In temperate climates, asthma peaks in the pollen season and again later in the year, while in the tropics, asthma increases in the wet season (Lancet editorial, 1985; LAIA 1993). In many asthmatic individuals, particular weather conditions can exacerbate an asthma attack. For example, in two US cities, daily hospital admissions for asthmatic attack were unusually high after the passage of a cold front followed by strong high pressure (Goldstein, 1980). Similarly, sandstorms in Kansas, USA and the Sudan have been accompanied by increases in bronchitis and asthma (Ayres, 1990).

The biological mechanisms via which inhaled small particles make people ill are unclear. Small particles can penetrate deeply into the lungs, causing bronchoconstriction and affecting respiratory mechanics. Children with persistent wheeze, asthma, chronic cough and chronic phlegm are particularly vulnerable to the health effects caused by inhalation of fine particulates (Schwartz et al., 1990). During periods of high PM_{10} concentrations and increased mortality, the numbers of visits to emergency rooms and hospitals by patients with a history of pulmonary disease rises (Utell, Frampton & Morrow, 1991; Xu, Dockery & Wang, 1991; Gold et al., 1993; Schwartz et al., 1993; Schwartz, 1995). Fine particulates may also provoke an inflammatory response in the respiratory alveoli (small air sacs), leading to increased fibrinogen levels in the bloodstream and contributing to reported particulates-related increases in the risk of cardiovascular events, including stroke, heart attack and angina pectoris (Seaton et al., 1995).

Research needs

If the world's climate changes, the number of heat-related deaths could rise significantly. The extent of such rises would depend on local geography, physiological acclimatization and the level of coping resources. Climate change could also cause a compensatory reduction in cold-related deaths, although in most populations this reduction would probably be less than the heat-related increase. Research on this particular question is deficient however.

Climate change can also be expected to lead to more frequent occasions when very hot weather combines with increased air pollutant concentrations and results in interactive effects — both in terms of the biological impacts on health and the physicochemical production of photochemical oxidants such as O_3. More generally, various respiratory disorders may be influenced by climate change.

Box 3.7. Weather/watch warning systems

The likelihood of more frequent episodes of thermal stress, particularly heat waves, due to climate change, underscores the need to develop health-related watch/warning systems. These systems can alert people to impending dangerous weather and also serve as a source of advice on how to avoid illness associated with weather extremes. More importantly, public health agencies can use the systems to guide them in their implementation of mitigation procedures during dangerous weather.

Such a system has been developed in the USA at the University of Delaware's Center for Climatic Research for Philadelphia and relies on the identification of "offensive" air masses that are associated with elevated mortality. The arrival of these air masses can be predicted up to two days in advance using forecast data, giving health officials time to broadcast warnings to the public and to initiate steps to reduce heat-related deaths. Additionally, statistical procedures can be used to estimate the number of deaths that the air mass will cause.

The system is activated on three levels. A "health watch" is issued by the Philadelphia Health Commissioner up to 48 hours and a "health alert" up to 24 hours before the expected arrival of the offensive air mass. A "health warning" is issued by the Health Commissioner, either the afternoon before or the morning of the forecast occurrence of an offensive air mass, if elevated mortality is anticipated. The local National Weather Service Office simultaneously issues a warning that very hot weather is forecast. A series of guidelines has been developed by the Philadelphia Department of Public Health, which indicates steps to be taken under each of the watch/warning system scenarios, as follows:

- activate hot lines so that people can obtain the necessary information during the heat emergency;
- initiate the "buddy system" whereby volunteers make daily visits to elderly people who may need assistance during hot weather;
- collaborate with the Philadelphia Corporation for Aging, which provides special services for elderly persons in need;
- contact local utility companies, to make certain that electrical services are not terminated for any individual during the heat emergency;
- contact the Philadelphia Water Department, to make certain that adequate water supplies are maintained during the heat emergency;
- contact radio and television stations, as well as newspapers, so that the public is notified rapidly of emergency conditions; additionally, the Department of Public Health should broadcast advice on how to avoid heat-related illness;
- advise nursing homes in the area that an emergency situation exists;
- open air-conditioned shelters for those who do not have access to cooler environments.

An evaluation of the watch/warning system is under way and a similar system may be introduced in Chicago. The US Environmental Protection Agency and the US National Weather Service are discussing the possibility of expanding the system nationally for the summer of 1997.

Sources: Kalkstein, 1995; Kalkstein, Jamason & Green, in press.

Much research is now underway to clarify these various causal relationships, and to improve the forecasting of climate change-related health impacts. In particular, there is a need to distinguish between the short-term and long-term effects of exposure to stressful weather and exposure to climate. Research is also needed on predisposing factors and the biological processes of temperature-related cardiovascular disease events, since these account for the majority of heat-related and cold-related morbidity and mortality events. The apparent population differences in intra-seasonality of acclimatization should be investigated too. Finally, the concept and utility of synoptic categorization of weather, to take effective account of its multiple dimensions, requires further development and validation.

Chapter 4

Effects on biological disease agents

Infectious disease patterns

Earlier this century infectious diseases generally appeared to be in broad retreat, at least in developed countries. But the "old" infectious diseases are now resurgent in many parts of the world (see Fig. 4.1). Incidence of food-related intoxications is also increasing. This situation reflects an unprecedented global convergence of a number of very diverse factors including rapid population growth, high-density human settlement on forest fringes, greater human mobility, long-distance trade, inappropriate use of pesticides and antibiotics, social and political disruption, and regional climatic disturbances.

Many of the biological organisms and processes linked to the spread of infectious diseases are especially influenced by fluctuations in climate variables, notably temperature, precipitation and humidity. Most of these fluctuations are part of normal climate variability, as evidenced by the "seasonality" incorporated in the survival strategies evolved by infectious disease agents, toxic organisms, vectors, reservoir species and pests. Climate change, with its considerable regional variation, can therefore be expected to cause widespread shifts in the pattern of a number of infectious diseases and in foodborne intoxication. For example, the net increases anticipated following climate change in the geographic distribution (both altitude and latitude) of vector organisms would increase the potential for transmission of many vector-borne diseases. Climate change would also alter the life-cycle dynamics of vectors and infectious parasites, further influencing transmission potential.

Distribution of disease agents that are neither transmitted by vectors, nor otherwise dependent on animal hosts, will probably also be affected by climate change, although our understanding of the processes that might be involved remains incomplete. The relevant diseases include the faecal-oral infections, many foodborne diseases, and infections spread directly from person to person. Evidently, in its passage from one individual to another, a pathogen is dependent on a specific mode of transmission and a particular configuration of various external factors. But temperature and humidity are crucial with respect to its reproduction, survival and infectiousness. Climatic factors also affect the contagiousness of infectious disease by influencing human and social behaviour. Thus even small changes in climatic conditions that are well within human tolerance levels, can have an indirect, adverse impact upon human health.

In short, predicting how climate change could alter the distribution and incidence of infectious diseases, and diseases caused by toxic organisms, will necessitate developing our knowledge of current climate–health relationships to the full, in particular concerning the seasonality of diseases, since this will highlight the effects of limiting factors.

Box 4.1. Direct effects of climate on vector biology

The direct effects of climatic variables on vector biology include the following:

- *Temperature:* An increase in temperature accelerates vectors' metabolic processes, consequently affecting their nutritional requirements. Blood-feeding vectors then need to feed more frequently. Their biting rate therefore increases which can, in turn, lead to increases in egg production. Temperature changes can also affect the distribution of many arthropod vectors since this is limited geographically by minimum and maximum temperatures (and humidities). Moreover, since most of the physiological functions of arthropod vectors are subject to optimal temperatures, any changes in minimum temperatures could greatly affect arthropod survival. For example, for several years in recent decades in the USA, warm winters precluded frost. Mosquitos, cockroach and termite populations increased as a result.

- *Humidity:* High relative humidity favours most metabolic processes in vector organisms. At high temperatures, a relatively high humidity prolongs the survival of most arthropods, although their susceptibility to fungal and bacterial infections may increase. Low humidity levels cause some vectors to feed more frequently to compensate for dehydration. In areas of high temperature and low humidity, triatomine bugs produce two generations per year compared with one generation per year in areas of lower temperature or higher humidity.

- *Precipitation:* Precipitation is an important factor with respect to insects such as mosquitos and blackflies. These insects have aquatic larvae and pupae stages, and it is precipitation that determines the presence or absence of breeding sites. The impact of precipitation on breeding sites depends on local evaporation rates, soil percolation rates, slope of the terrain, and proximity of large water bodies and rivers. Many species breed in the residual water that remains after flooding in the rainy season. However, extremely heavy precipitation will wash vector larvae away, or kill them directly. Well-oxygenated water is crucial for blackfly breeding; it is typically associated with rapidly-flowing streams and small rivers on hills. Other vectors, however, such as *Aedes aegypti* (a vector of dengue), are adapted to urban environments, breed in water containers and relatively unaffected by precipitation.

- *Wind:* Since winds contribute to the passive dispersal of flying insects, prevailing wind directions and wind speeds affect vector distribution. Some insect vectors, including various *Anopheles* species (malaria mosquitos), Simuliidae (blackflies) and Phlebotominae (sandflies), can thus be dispersed hundreds of kilometres from their original area.

Sources: Hack, 1955; Wilke, 1995.

Disease vectors and intermediate hosts

The range of human infectious diseases is wide. The infective agent or parasite can be a virus, a bacterium, a single-celled organism (protozoa) or a multi-celled organism (such as a fluke). In the case of vector-borne diseases, a vector "incubates" and transmits the infective agent between humans. The vector is typically a cold-blooded organism, such as an insect, tick, snail or crustacean; its geographical distribution and vectorial capacity are the two most important determinants of disease transmission (Longstreth, 1989). For vectors with long lifespans — for example, tsetse flies, bugs, and ticks — vector abundance is an additional major determinant of disease distribution. But for vectors with short lifespans, such as mosquitos, sandflies and blackflies, the temperature-sensitive extrinsic incubation period is of more importance.

Sustained (or endemic) transmission in a particular area of vector-borne disease depends on the presence of an adequate vector population, and favourable environmental conditions for both vector and parasite. An intermediate host species may also be necessary. The distribution and abundance of vectors and intermediate host species are influenced by mean climate variables (temperature, precipitation, humidity, surface water and wind), climate variability and extreme events (such as excessive precipitation). Biotic factors, such as vegetation, and populations of host species, predators, competitors and parasites, and human interventions, are also important influences (see Boxes 4.1 and 4.2) (WHO, 1990b). Similarly, various non-vector-borne parasitic diseases such as ankylostomiasis (hookworm disease) involve a free-living developmental stage

Box 4.2. Indirect effects of climatic variables on vectors

Climate change is likely to have indirect effects on vector abundance and vector populations. For example, a vector species may be displaced by another vector species following shifts in environmental conditions. As the vectorial capacities of the original and displacing species may differ considerably, the effect of species replacement on disease transmission will depend on the particular species involved.

Several *Anopheles* species, and in some cases the malaria they transmit, have disappeared from previously thickly forested areas following deforestation which removed the flora and fauna upon which they depended. Examples include *An. dirus* in Thailand and *An. darlingi* in South America. The survival of ticks and mites likewise depends on local flora and fauna — for shelter that provides an appropriate microclimate and for specific host species for feeding.

But other species have clearly benefited from habitat changes. For example, deforestation in the Indo-Australian region has enabled all three species of the *An. punctulatus* group to establish themselves, resulting in "human-made" malaria. Changes in agricultural practices associated with climate change may also affect vector abundance. Introduction or expansion of irrigation in areas affected by drought or decreased precipitation, would increase the number of breeding sites for mosquitos, and also increase snail populations and the risk of schistosomiasis. Sea level rise and increased coastal flooding may result in greater quantities of brackish water which would favour vector species such as *An. subpictus* and *An. sundaicus*, since these prefer brackish water for breeding.

Box 4.3. Climate change and vector-borne disease distribution

The following factors in particular must be considered when attempting to predict the effect of global climate change on the distribution of vector-borne diseases:

- the current geographic distribution of the disease;
- the range of non-human hosts and reservoirs (i.e. insect or mammal);
- temperature-related vector and parasite development, and adaptive processes pertaining to reservoir and parasite interactions;
- capacity for migration of vectors and parasites;
- the current seasonality of transmission.

Source: Shope, 1991.

outside the host, that is sensitive to temperature and moisture. So there are many factors relating to infectious disease that could be affected by climate change and even increased ultraviolet radiation (UVR).

Indeed, palaeoclimatic records of insects from the Quaternary period demonstrate that most shifts in the distribution of several insect taxa have been associated largely with temperature change. Moreover, these shifts appear to have occurred much more rapidly than shifts in the distribution of vegetation and higher animals (Elias, 1994; 1995). Fossil records from the end of the last glaciation (10 000–15 000 years ago) show shifts in distribution of insect species across latitudes that correlate with fluctuations in minimum temperatures, identified through examination of Greenland ice-core data. This further suggests that the current geographical distribution of many of the organisms that act as vectors of infectious disease in humans would shift following any future climate change (see also Box 4.3).

Nevertheless, although climate dictates the distribution of most vector-borne diseases, and will doubtless continue to do so, local weather conditions often constitute the principal determinant of the timing and intensity of disease outbreaks. This is because vectors and infective agents are affected by ambient temperatures and humidities (Gillet, 1974; Dobson & Carper, 1993).

Vector-borne disease incidence and control

In tropical countries especially, vector-borne diseases are a major cause of illness and death. Estimates of the number of people at risk from and the number of people who are currently affected by the world's major vector-borne diseases are given in Table 4.1. Currently, the distribution of most vector-borne diseases remains well within the climatic limits of their vectors. This is in part due to biological restrictions that limit the survival of the infective agent in the vector population and in part to certain human activities, such as drainage, urbanization, and control of water pollution, that help to prevent the spread of pathogens and also contribute to reduction of vector populations. Conversely, local environmental changes due to deforestation, agriculture and water resource development, have caused massive increases in the incidence of vector-borne diseases. In particular, failure to incorporate health safeguards in the design and implementation phases of large-scale development projects has often resulted in the creation of new habitats for vectors and, consequently, intensified transmission (Stanley & Alpers, 1975; IRRI/WHO/FAO/UNEP, 1988; Tiffen, 1989;

Table 4.1. Major tropical vector-borne diseases and the likelihood of change in their distribution as a result of climate change

Disease	Vector	No. at risk (millions)[a]	Number infected or new cases per year	Present distribution	Likelihood of altered distribution with climate change
Malaria	Mosquito	2400	300–500 million	Tropics/subtropics	+++
Schistosomiasis	Water snail	600	200 million	Tropics/subtropics	++
Lymphatic filariasis	Mosquito	1094	117 million	Tropics/subtropics	+
African trypanosomiasis	Tsetse fly	55	250 000–300 000 cases/yr	Tropical Africa	+
Dracunculiasis	Crustacean (copepod)	100	100 000/yr	South Asia/Middle East/ Central–West Africa	?
Leishmaniasis	Phlebotomine sandfly	350	12 million infected, 500 000 new cases/yr[b]	Asia/south Europe/ Africa/Americas	+
Onchocerciasis	Blackfly	123	17.5 million	Africa/Latin America	++
American trypanosomiasis	Triatomine bug	100	18–20 million	Central–South America	+
Dengue	Mosquito	2500	50 million/yr	Tropics/subtropics	++
Yellow fever	Mosquito	450	<5000 cases/yr	Tropical South America and Africa	++

+ = likely; ++ = very likely; +++ = highly likely; ? = unknown

[a] Top 3 entries are population-pro-rated projections, based on 1989 estimates.

[b] Annual incidence of visceral leishmaniasis; annual incidence of cutaneous leishmaniasis is 1–1.5 million cases per year.

Sources: PAHO, 1994; WHO, 1994a; 1995; Michael & Bundy, 1996; WHO statistics.

Walsh, Molineaux & Birley, 1993; Lines, 1995). Therefore, the extent to which disease transmission potential shifts geographically in response to shifts in vector distribution following climate change will depend partly on how human activities modify local ecosystems.

Rodent-borne diseases, that could be affected by climate change include plague and hantavirus pulmonary syndrome. In a warmer and more urbanized world, rodent populations which act as pathogen reservoirs, and as hosts for the relevant arthropod vectors, will tend to increase. Incidence of these diseases can thus be expected to rise (Shope, 1991).

Disturbances of ecological relationships due to climate change could also influence the global pattern of vector-borne diseases. For example, shifting distribution ranges of animal species would create new mixtures of different species, thereby exposing suitable hosts to new pathogens and vectors. The natural control mechanisms of vector, intermediate host, reservoir and parasite populations may also be disrupted, leading to altered population dynamics and accelerated selection of pesticide resistance in vectors and drug resistance in infectious agents. Additionally, more frequent droughts and rising sea levels, which are anticipated with climate change, might displace human populations into areas where zoonotic infectious agents are currently being transmitted in silent wildlife cycles, and without significant clinical manifestations in humans. Some migrant populations would therefore be at new risk of infection with enzootic agents. Changing climatic factors could also contribute to the emergence and re-emergence of infectious diseases (Patz et al., 1996) (see Box 4.4 and Fig. 4.1).

Box 4.4. Emerging infectious diseases

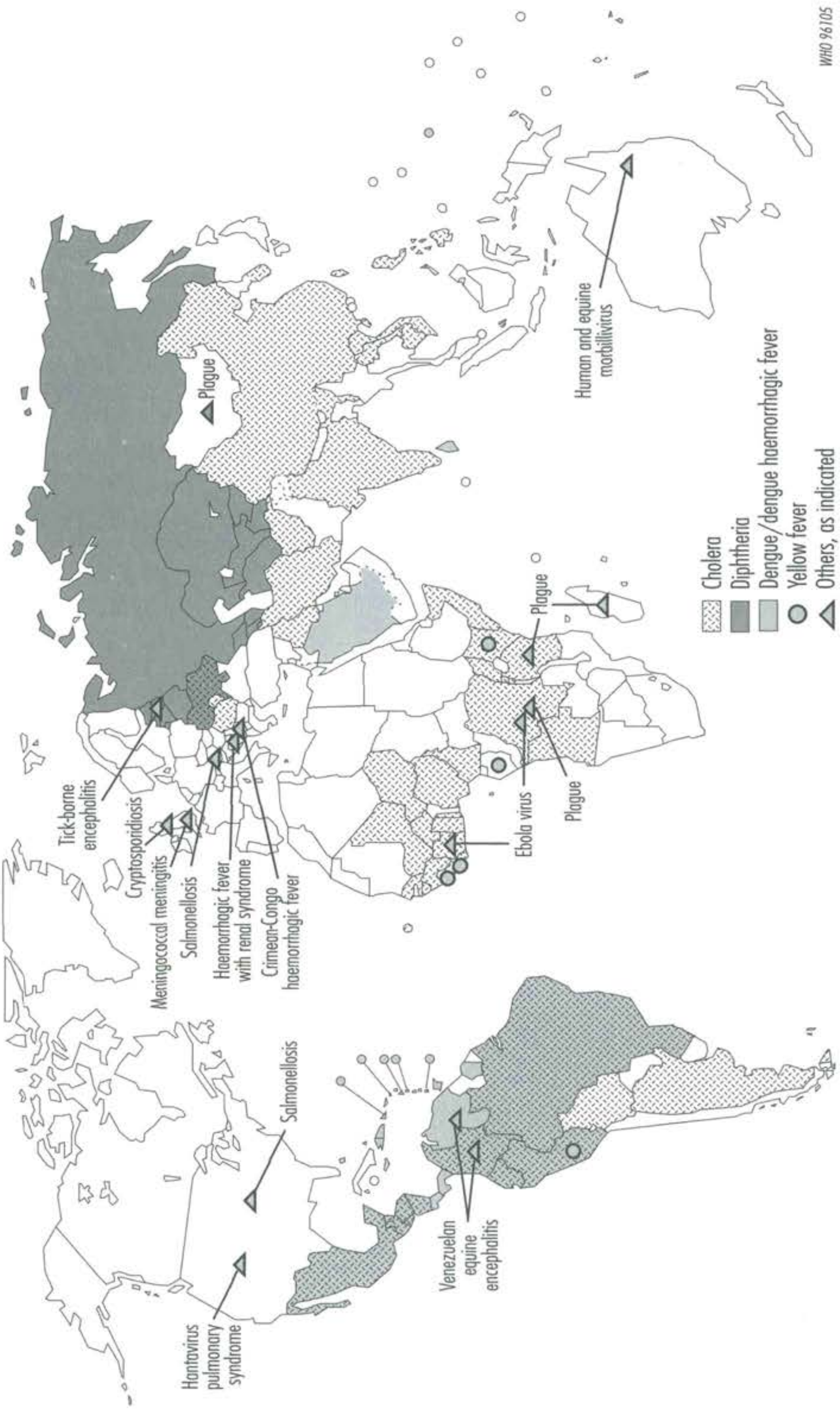
Emerging infectious diseases are infections that are new in the population under consideration, rapidly increasing in incidence or expanding in geographical range. Most emerging infectious diseases are caused by changes in "microbial traffic" — that is, the introduction of existing agents into or the dissemination of existing agents among human populations. These agents may be from other geographic areas, or transmitted from an animal reservoir or from smaller human populations such as indigenous groups living in remote, isolated areas. Factors contributing to the emergence of infectious diseases often relate to the following:

- *Environmental change:* deforestation/reforestation; habitat loss/fragmentation; changes in water ecosystems and water distribution; flood/drought; famine; climate change.
- *Socioeconomic change:* economic decline; violent conflict; population growth and migration; urban decay.
- *Health care:* new medical interventions; organ or tissue transplantation; drugs causing immunosuppression; widespread use and abuse of antibiotics.
- *Food production:* globalization of food supplies; changes in food processing and packaging.
- *Human behaviour:* sexual behaviour; drug use; travel; diet; outdoor recreation.
- *Public health infrastructure:* curtailment of or reduction in prevention programmes; inadequate surveillance of communicable diseases; lack of trained personnel (epidemiologists, laboratory scientists, vector and rodent control specialists).
- *Microbial adaptation and change:* changes in virulence and toxin production; development of drug resistance; microbes as co-factors in chronic diseases, such as rheumatism and cardiovascular disease.

Recent examples of emerging infectious diseases include: dengue in Costa Rica, hantavirus pulmonary syndrome in the USA (see Box 4.6), yellow fever in Kenya, and a new variant of cholera. Diseases involving vectors such as insects and rodents respond quickly to climatic, ecological and social change. In May 1995, the World Health Assembly (the supreme governing body of WHO) adopted two Resolutions (WHA48.7; WHA48.13) calling on WHO to modify the *International health regulations* so as to take account of faster and more voluminous international traffic and trade, and on Member States to tighten disease surveillance systems, in order to cope more effectively with these new, emerging and re-emerging infectious diseases.

Sources: Morse, 1991; CDC, 1994d; Levins et al., 1994; Epstein, 1995a.

Fig. 4.1. Selected emerging and re-emerging disease outbreaks in 1995



Source: WHO, 1996.

Evidently, effective public health programmes, using control methods such as quarantine, vaccination, drug treatment and pesticide application, can limit the geographical distribution of vector-borne diseases. But the continued use of some of these control methods could themselves present a number of risks. For example, long-term application of pesticides may favour the emergence of resistant vector strains, while at the same time destroying predator populations that under normal circumstances would contribute to restricting the size of vector populations. Other methods of disease control such as integrated environmental management hold much more promise and are particularly appropriate when combined with activities such as sustainable water resources development (Cooper Weil et al., 1990; Hunter et al., 1993).

The following sections review current knowledge of the climatic determinants of infectious diseases and understanding of the potential impacts of climate change on a number of vector-borne diseases. These examples are not comprehensive. The aim is to present a sufficiently wide variation of epidemiological situations to illustrate how climate change might affect disease incidence.

Malaria

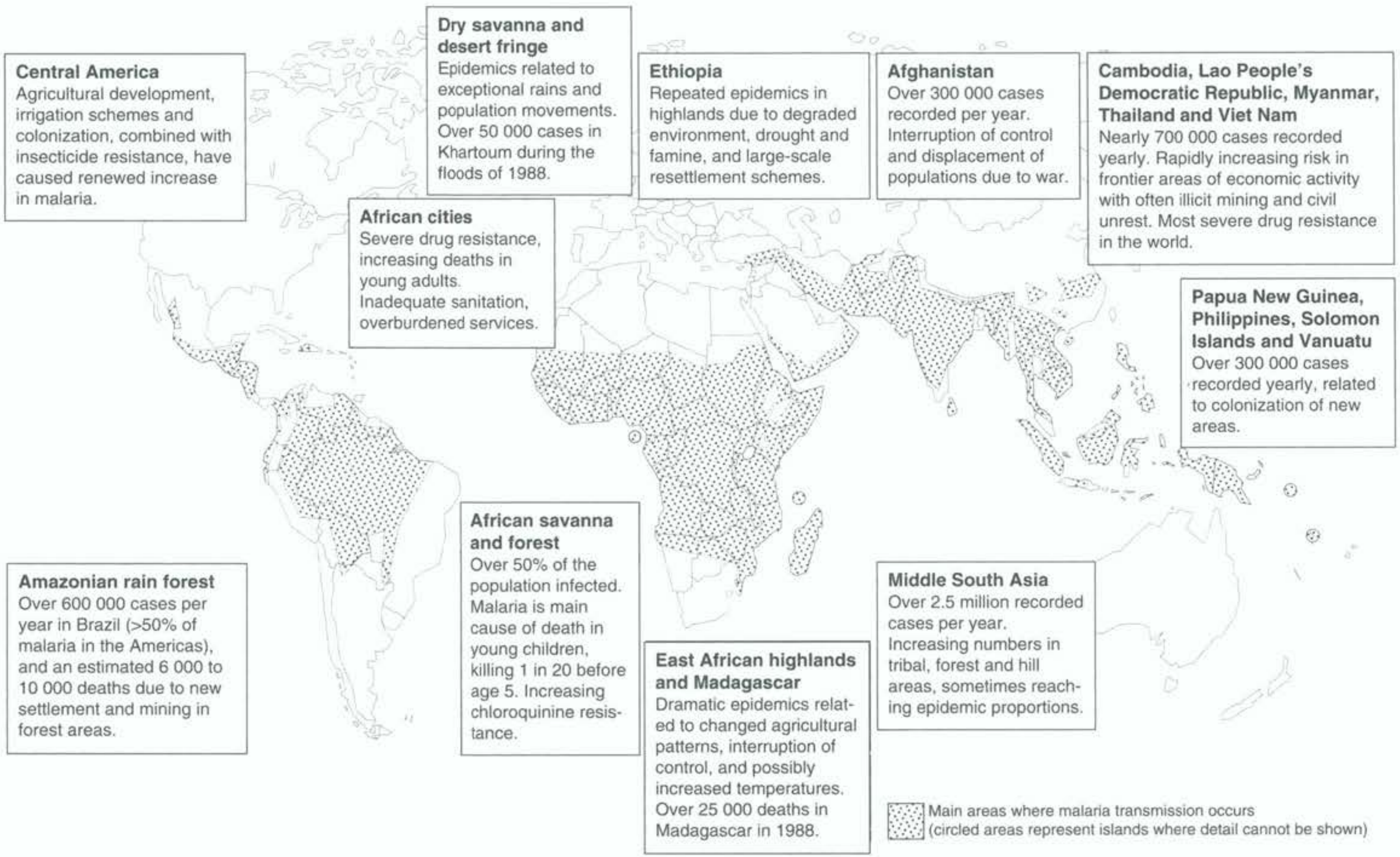
Up until World War II, many parts of today's developed world were malarious, including the USA, western and southern Europe, and northern Australia. Indeed, malaria outbreaks occurred in Scandinavia and England as late as the 19th century. An estimated 1 in 20 people in the world are currently infected with malaria, with approximately 350 million new cases occurring annually (see Fig. 4.2). An estimated 2 million die from malaria every year, including more than a million young children, a large proportion of these in Africa (WHO, 1995a).

Malaria is caused by four species of the plasmodium parasite; *Plasmodium vivax* has the broadest geographical range and *P. falciparum* is the most dangerous clinically. The parasite is transmitted between humans by female, blood-feeding mosquitos. The plasmodium completes its several, asexual, life-cycle stages in the human liver and in red blood cells, and then undergoes sexual development and sporogony in the mosquito.

Control of malaria is becoming increasingly difficult and manifestations of the disease appear to be more severe than in the past. Chemotherapy options have narrowed since the most virulent species, *Plasmodium falciparum*, and more recently *P. vivax*, have become increasingly drug-resistant. Following two decades of research, several candidate malaria vaccines are currently undergoing field-testing by WHO and the UNDP/World Bank/WHO Special Programme on Research and Training on Tropical Diseases. According to an analysis made by WHO (1993a), efforts to control malaria are meeting with less and less success due to the various combinations of socioeconomic, geographical and ecological conditions prevailing in the tropical world (see Fig. 4.2). In many regions where malaria transmission had been almost eliminated, the disease has made a comeback, sometimes surpassing earlier recorded levels.

WHO recently adopted a global strategy for malaria control, based on recognition of eleven broad geographic problem areas, each requiring different control approaches in accordance with technical possibilities and economic realities (WHO, 1993a). The strategy aims to prevent malaria mortality, and to reduce the morbidity and social and economic losses associated with the disease. It also seeks to strengthen local capacity in basic and applied research so as to enable countries to assess malarial incidence, prevention and control regularly, and to identify the specific ecological, social and economic determinants of the disease that pertain to their countries. Adopted by the

Fig. 4.2. Malaria distribution and problem areas



Source: WHO, 1993a.

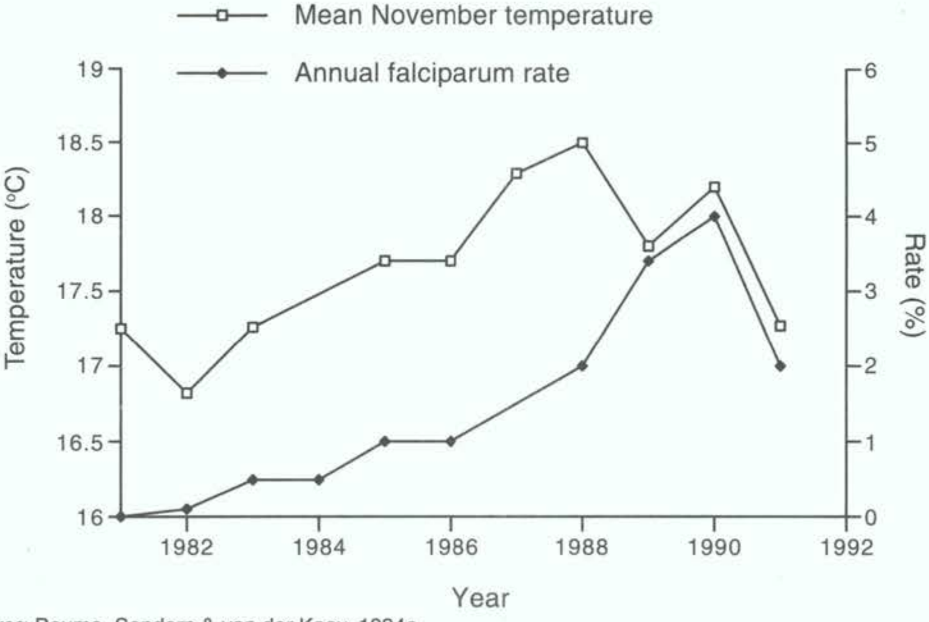
World Health Assembly in May 1993, this rather optimistic strategy thus recognizes the need to improve understanding of how climate-related and other ecological factors affect the spread and severity of malaria.

Recent evidence of the responsiveness of malaria incidence to local climate change and perturbations includes marked increases in the incidence and distribution (particularly with reference to altitude) of malaria during atypically hot wet weather in Rwanda in 1987 (Loevinsohn, 1994). Similarly, annual fluctuations during the 1980s in falciparum malaria intensity in north-east Pakistan correlate with variations in annual temperature and precipitation experienced during those years (Fig. 4.3) (Bouma, Sondorp & van der Kaay, 1994a; Bouma, 1995).

Temperature, precipitation and extreme weather events can also have an effect on the viability and geographical distribution of the anopheline mosquitos that transmit malaria. Some higher latitude species are able to survive in sheltered places during cold spells, but most anopheline mosquito activity comes to a halt when the temperature drops below 22°C (Carcavallo et al., 1995). Moreover, several species that transmit falciparum malaria generally do not survive when mean winter temperature drops below 16–18°C. Warming could therefore be anticipated to increase mosquito survival rates in temperate areas. However, since mosquito survival rates become more sensitive to relative humidity at higher temperatures, warming without additional precipitation may serve to reduce mosquito longevity and to decrease malaria transmission in tropical regions.

The extrinsic incubation cycle of the plasmodium is particularly sensitive to temperature; this sensitivity is an important limiting factor in disease transmission (Macdonald, 1957). Optimum temperatures for the sexual development of the various species of the malarial plasmodium in the

Fig. 4.3. Variations in November temperature and annual falciparum malaria rate in north-east Pakistan between 1981 and 1991



Source: Bouma, Sondorp & van der Kaay, 1994a.

Fig. 4.4. Critical temperatures in malaria epidemiology (°C)

minimum temperature for mosquito development

optimum temperature for mosquitos

8 9 10 . . . .14 15 16 17 18 19 . . . . .25 26 27 40

minimum temperature for parasite development
P. vivax < P. falciparum

maximum temperature for parasite and mosquito

mosquito are: 25°C for *P. vivax*; 30°C for *P. falciparum* and 22°C for *P. malariae* The plasmodium does not develop at temperatures outside the 14–38°C range. Sporogonic development of *P. vivax* ceases below 14–16°C, and below 18–20°C for *P. falciparum*. (Minimum temperatures vary between different local strains) (see Fig. 4.4). Thus even a slight increase in minimum average temperature would accelerate extrinsic incubation greatly (Miller & Warrell, 1990).

While it is principally temperature that determines survival rates of both the vector and the parasite, precipitation directly influences the abundance of breeding sites and vector densities. (It also affects vector survival through its effect on humidity.) For example, in puddle-breeding species, such as those of the *Anopheles punctulatus* group in the Indo-Australian area, breeding site availability is closely associated with daily precipitation (Slooff, 1961). And during serious drought, massive numbers of puddles created in drying river beds can lead to vector explosions, as was the case with the *An. culicifacies*-associated epidemics in Sri Lanka during 1934 and 1935 (Pampana, 1963; Bouma, 1995). However, for *An. darlingi* in the forests of Surinam, the availability of breeding sites is more dependent on river water tables remaining within certain upper and lower levels, than upon precipitation *per se* (Rozendaal, 1990).

The geographical distribution of malaria is also dependent to some extent on factors other than temperature and humidity. Anopheline populations must be viable and alternative host animals available, for instance. Similarly, the intensity of transmission will vary in accordance with the aforementioned factors, while human behaviour and the level of health care facilities available will serve to increase or decrease transmission potential. For example, in tropical areas, environmental management and vector control using biological and chemical pesticides have proved highly effective in decreasing transmission (WHO, 1993a). Conversely, incidence increases when surveillance and preventive health care are lacking or inadequate.

Mathematical models of the potential impact of climate change on malaria

Quantitative estimates of the impacts of climate change on the potential transmission of malaria have been made using mathematical models (see Chapter 9). The term "potential" is here used to refer to the models' predictions of where malaria could occur as a function of climate and associated environment. That is, the models do not take local demographic, socioeconomic and technical circumstances into account that could limit transmission.

A simple model has been used for Indonesia, based on historical data from selected provinces on the relationship between annual average temperature and total annual precipitation, and malaria incidence (Asian Development Bank, 1994). The model forecasts that the current annual malaria incidence rate of 2705 per 10 000 persons would, under a mid-range climate change scenario, increase marginally by the year 2010, and by approximately 25% by the year 2070. These estimates assume that efforts in Indonesia to prevent or control malaria will remain constant. However, owing to the limited technical information given, appraising these particular forecasts is difficult.

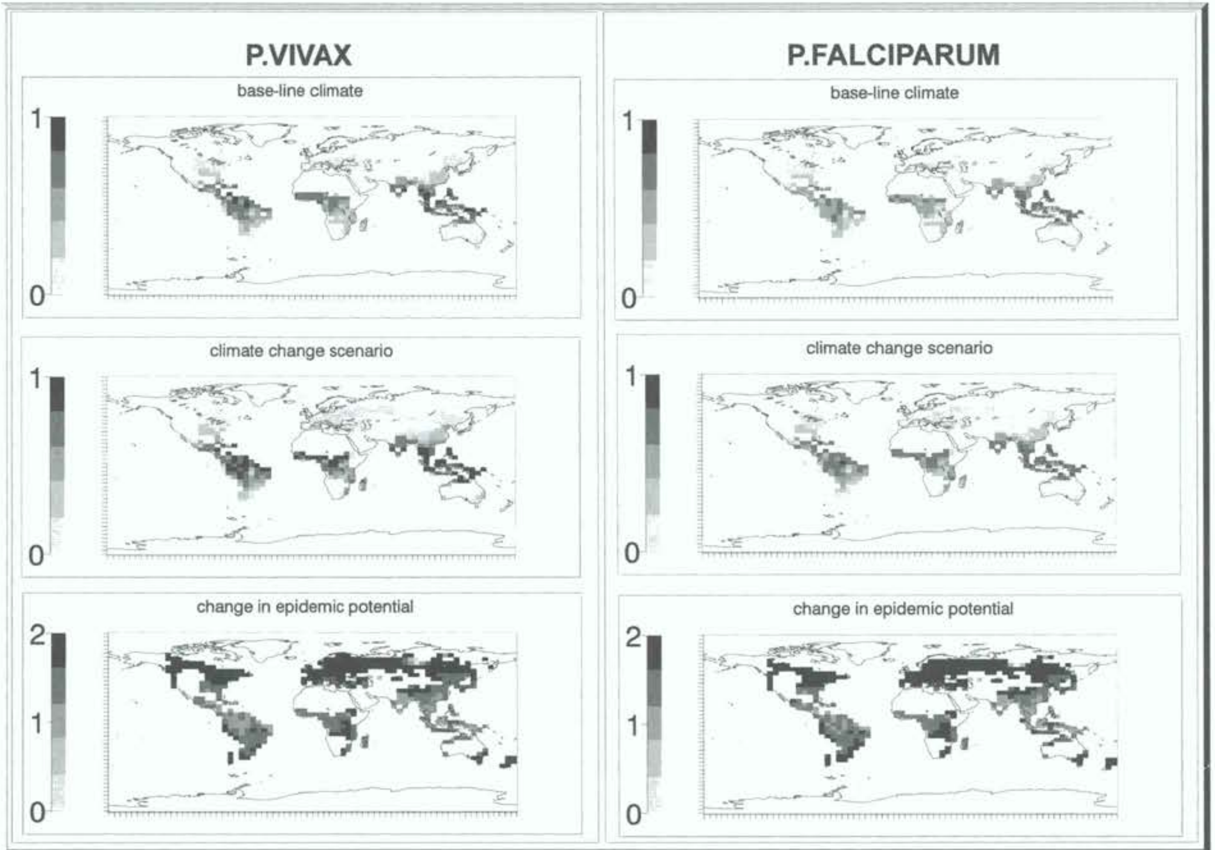
Aggregated models have also been developed. These can be used to make quantitative predictions of climate-related changes in the global distribution of malaria vectors (see Chapter 9; Box 9.3). Most of these models predict a net increase in the geographical distribution of potential malaria transmission (Sutherst, 1993; Matsuoka & Kai, 1994; Martin & Lefebvre, 1995).

Clearly, widespread shifts in anopheline habitat, accompanied by changes in vectorial capacity could increase malaria transmission potential worldwide (Martens, Rotmans & Niessen, 1994). However, the level of immunity within the population is also a critical determinant of the numbers of cases. In highly endemic areas, with high immunity, the impact of a climate-related increase in malaria transmission would be less than in populations with initially low levels of immunity. In areas with initially unstable malaria, a climate-induced increase in reproduction rate could render transmission more stable. At higher altitudes, such as the eastern highlands of Africa, or in the Andes region of South America, an increase in temperature of several degrees centigrade could increase the transmission potential sufficiently to convert initially malaria-free areas into areas that experience seasonal epidemics (Martens et al., 1995a). Large urban highland populations that fall just outside areas of stable endemic malaria and that are currently essentially malaria-free would be affected most. Examples include cities such as Nairobi in Kenya and Harare in Zimbabwe. Given that mosquito populations respond rapidly to climate change, the introduction of malaria into populations such as these would constitute early evidence of climate-related shifts in the distribution of this disease (Taylor & Mutambe, 1986; Haines, Epstein & McMichael, 1993) (see also Chapter 9).

Martens et al. (1995b) have estimated that an increase in global mean temperature of several degrees by 2100 would increase the vectorial capacity of mosquito populations in tropical countries two-fold, and more than 100-fold in temperate countries. However, in temperate countries, continued and increased application of effective control measures such as disease surveillance and prompt treatment of cases would probably counteract any increase in vectorial capacity. Climate change is therefore unlikely to recreate a state of endemicity in these countries, although growing resistance of mosquitos to pesticides may interfere with chemical vector control.

The modelling studies by Martens et al. (1995a) have predicted the impacts of climate change *per se* on distribution and incidence of malaria, assuming that all other factors are held constant. Fig. 4.5 presents the global distribution of potential malarial risk areas for the current climate and for two GCM-based climate change scenarios. As can be seen, the greatest changes in potential *vivax* malaria risk relative to 1990 are predicted to occur in temperate zones. A climate-induced increase in malaria prevalence of 50–80 million cases is forecast in response to a global mean temperature rise of around 3°C by the year 2100, compared to a projected prevalence of approximately 500 million cases in 2100 in a world that does not undergo climate change (Martens et al., 1995b). In general terms, the modelling results show that by the latter half of the next century, the percentage of the world population living within the *potential* malaria transmission zone will have increased from 45% to around 60% (Martens et al., 1995a).

Fig. 4.5. Potential malaria risk areas for base-line climate conditions (1831–1980) and for a global mean temperature increase of 1.16°C (based on the climate patterns generated by the ECHAM1-A GCM) and changes in average annual "epidemic potential" (EP), a measure of vectorial capacity, relative to base-line climate, for *P. vivax* and *P. falciparum*.



Source: Martens et al., 1995b. Reproduced with kind permission from W.J.M. Martens.

It is probable that climate change would cause malaria (particularly *P. falciparum*) to extend its spread by both latitude and altitude in tropical countries (Martens, Rotmans & Niessen, 1994). It may also affect the malaria transmission patterns in these countries. For instance, transmission could start to occur throughout the year if breeding sites — in combination with temperatures favouring transmission — became available year-round as opposed to seasonally only. However, if seasonal differences in patterns of temperature and precipitation became more marked, the opposite may apply.

Studies by Martin & Lefebvre (1995), using another mathematical model, also predict that malaria transmission would spread to higher latitudes. However, their studies indicate that some currently stable endemic areas near the equator would become unstable, due to reductions in mosquito longevity, as a result of yet higher temperatures, and result in reduced population immunity levels. Initially, the vulnerability of communities newly exposed to malaria in areas previously malaria-free would lead to high case-fatality rates. Acquired immunity levels would later provide some protection.

It should be noted that although the models described here account only for the impact of climate change *per se*, interpretation of the results of global integrated models must take into account local conditions such as control measures, health services, parasite reservoirs, and mosquito densities. Moreover, model results should be treated with caution until they have been validated against historical data sets. Incorporation of more extensive detail into the models is also required. Despite these difficulties, however, mathematical models provide a feasible means of studying the impact of climate change on vector-borne diseases and elucidating the interdependent relationships between climate change, vector population dynamics and human disease dynamics (see also Chapter 9).

Local vector ecology: the case of Argentina

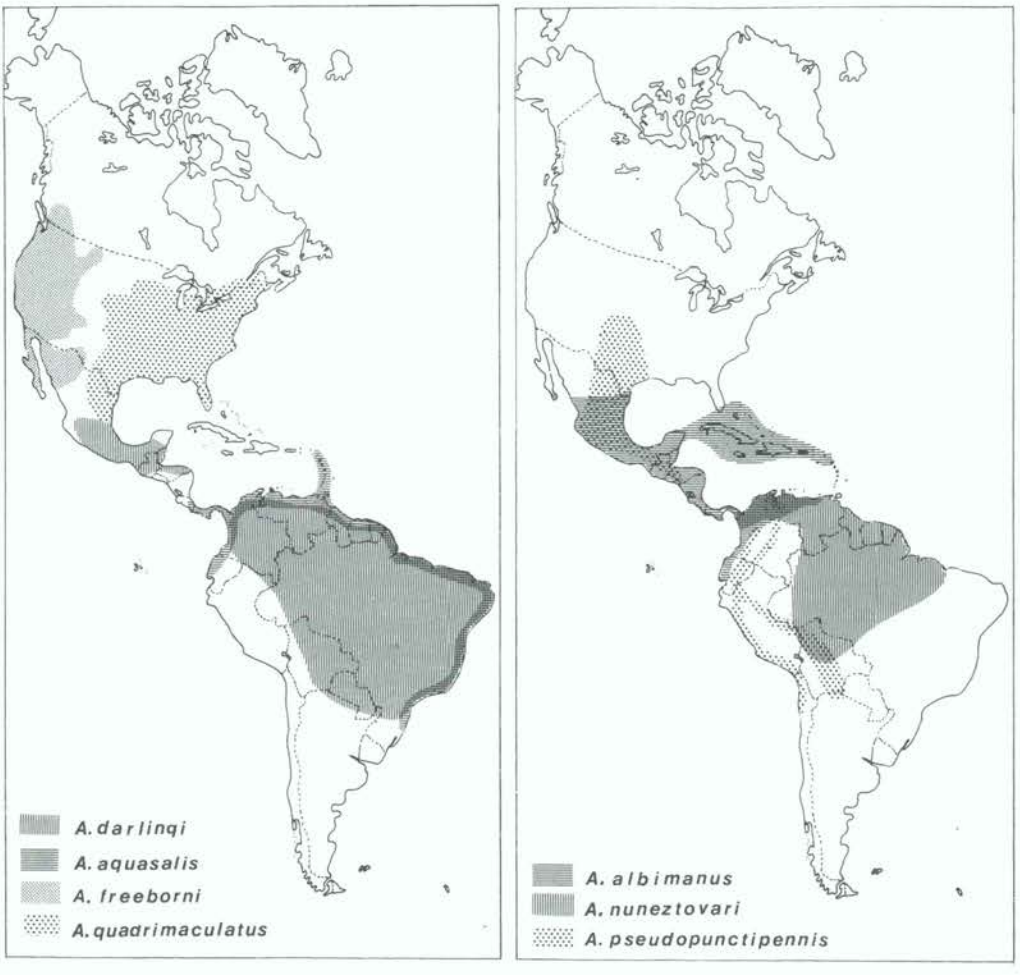
Further improvement in forecasting the impacts that a warmer climate may have on malaria incidence requires development of ecological models, capable of taking into account the biological differences between vector species. To illustrate the importance of considering local ecological conditions, this section focuses on Argentina, a country that may become subject to greater increased incidence of malaria as a result of climate change.

Compared with other countries in the Americas, Argentina does not at present have a serious malaria problem. However, the malaria vectors in the northern part of the country provide the basis of an ideal case study of the disease at its current southern limit on this continent. The present geographical distributions of the principal vectors of malaria in North and South America are illustrated in Fig. 4.6. The main malaria vectors in South America are: *An. darlingi*, *An. pseudopunctipennis*, *An. albitarsis*, and species of the *An. (Kerteszia)* subgenus.

Variations in temperature, precipitation, humidity and winds associated with global climate change would affect both the geographical dispersion and behaviour of vector species in temperate regions of South America (Burgos et al., 1994a; 1994b). Climate change experiments indicate that some areas of central Argentina, such as the Pampa region and savannas, may become subtropical, particularly if precipitation increases by more than 10% (Hansen et al., 1987, 1988). The western region of Argentina may become warmer and drier, with precipitation similar to or less than that experienced at present (Pittock & Salinger, 1982; Pittock, 1983).

In human-made ecosystems, such as cities or areas of intensive agriculture, vector species have adapted and are able to spend much of their life cycle in artificial shelters with buffered microclimates, thereby protecting themselves from some climate extremes. But in natural ecosystems, vector populations are sensitive to climate, the vegetation type, food availability, and pressure from predator and pathogen populations. Wild vector species (that is, species not adapted to life in the urban or domestic environment) could thus be displaced by increased temperatures and changed precipitation patterns to new areas where breeding sites, microclimate, food and shelter favour their survival, which could result in further ecosystem disturbance. The human-assisted intercontinental migration and subsequent successful colonization of new habitats in the Americas by *An. gambiae* (from Africa) in the 1960s and the rapid and ongoing invasion of all continents by *Ae. albopictus* (from Asia) in the 1980s and 1990s, is proof that at least some mosquito species can establish themselves in distant new environments within decades.

Fig. 4.6. Principal vectors of malaria in North, Central and South America



Source: WHO, 1989.

For *An. darlingi*, preferred breeding sites include shaded creeks, river edges, flooded forests and pools in river beds. Its distribution is associated therefore with heavy precipitation and flooded forest areas (Bejarano, 1971; Rozendaal, 1990). Any increase in temperature and precipitation in the Argentinean temperate region would probably lead to an expansion of its range. Additionally, this vector species could reach higher altitudes, extending its geographical distribution to the western Argentine foothills. But in the west, decreased precipitation and an increased risk of desertification would probably reduce population density and dispersal rates.

As for *An. darlingi*, the distribution of *An. pseudopunctipennis* is associated with heavy precipitation. *An. pseudopunctipennis* is the most important malaria vector in many areas of South America, with a distribution extending from south-east Mexico to north-west Argentina. In Peru, it is found between 250 and 3200 m above sea level, particularly in subtropical valleys and foothills (Bejarano, 1967). It breeds in clear, still water, small streams or irrigation canals, and feeds upon humans and animals, in both domestic and wild environments. Mosquito density is thus very high at the end of the rainy season (Carcavallo et al., 1995). In the north-west of Argentina, desertification caused by climate change could thus reduce its geographical distribution, resulting in fewer malaria outbreaks. Alternatively, the species could respond by shifting its distribution to the central hills of Argentina, in order to find small rivers that provide suitable conditions for reproduction.

Unlike *An. pseudopunctipennis*, *An. albitarsis* is a poor vector of malaria. Nevertheless it is significant because of its high population densities and wide distribution. Low winter temperatures currently prevent expansion of this distribution (Burgos et al., 1994b). This species' ideal breeding sites are fresh and stagnant waters in sunny places, with aquatic vegetation. It feeds in both wild and domestic environments and prefers shady places by day. The effects of an increase in temperature and precipitation might be similar to those predicted for *An. darlingi*, namely, higher population densities and an extended distribution to the south. In short, endemicity would be maintained and the area of epidemic malaria extended.

Currently, the extreme north-east of Argentina forms the southern limit of the geographical distribution of *An. (Kerteszia)* spp. Their larvae develop in water collected in plants (mostly *Bromelia* spp.) which abound in the rain forest. The mosquitos transmit malaria to forest workers and indigenous people. Extension of the geographical distribution of *An. (Kerteszia)* spp. would occur only if temperature and precipitation increased, and the area of suitable vegetation expanded.

American trypanosomiasis

American trypanosomiasis (Chagas disease) is a parasitic disease caused by the parasite *Trypanosoma cruzi*, and transmitted by blood-feeding, "kissing" bugs of the subfamily Triatominae, of the family Reduviidae. The geographical distribution of the disease is limited to the Americas, ranging from the southern USA to southern Argentina and Chile. The number of people currently at risk of the disease is 100 million; 18 million people are currently infected (WHO, 1995c). The disease is a major public health problem in South and Central America since 8–10% of the rural and poor urban population is affected. An estimated 15–20% of those who contract the disease develop its digestive, neurological or cardiac manifestations, which cause thousands of deaths annually. Chagas disease and its vectors are already undergoing shifts in distribution in Latin America due to ecological and demographic changes. The spread of urban slums and transmission through blood transfusion are significant factors in this redistribution (Almendares et al., 1993).

Most triatomine vector species are tropical or subtropical; optimal temperatures for reproduction and their survival in general are between 26°C and 29°C; optimal relative humidity is 70%. The minimum temperature required for feeding, dispersal and reproduction is 20°C (Curto de Casas & Carcavallo, 1984). Several studies have demonstrated that triatomine bugs are sensitive to small variations in temperature and humidity (Clark, 1935; Gamboa, 1962, 1974; Alarcón, 1980). Experimental studies, for instance, indicate that at higher temperatures of around 28–30°C, the vectors feed more frequently, have a shortened life cycle, and increase in population density (Carcavallo & Martínez, 1972; 1985). Bugs reared at increased temperatures also feed and mate more frequently, leading to a greater population density and a higher rate of egg-laying. If temperature exceeds 30°C, and humidity does not increase sufficiently, the bugs increase their feeding rate to avoid dehydration.

Analysis of the life cycles of several triatomine species could be helpful in predicting the impact of climate change on ecosystems. Attempts have been made to classify the geographical distribution of the tropical vector species taking into account microclimatic factors such as temperature, dryness (in relation to humidity and evapotranspiration) and precipitation (Curto de Casas et al., 1994).

Higher temperatures could extend the geographical distribution of wild vectors of Chagas disease, by both latitude and altitude. Higher humidity may also increase the geographical distribution of species that are prevalent in tropical and subtropical forests. However, lower humidity — although possibly extending their geographical distribution and increasing their population densities — may shorten the life cycle of those species found in dry tropical and subtropical forests, and in arid areas. Should indoor temperature rise, vector species in the domestic environment may develop shorter life cycles and higher population densities. However, for domestic vector species of Chagas disease, human activities, such as replastering of walls and use of chemicals, are more significant than climate in terms of determining population density.

Human African trypanosomiasis

Human African trypanosomiasis, also known as sleeping sickness, is transmitted by the blood-feeding tsetse flies of the Glossinidae family, of which more than twenty species are known. Tsetse flies do not depend on aquatic habitats; newly-born larvae burrow themselves in topsoil under vegetation cover, and re-emerge as adults after a short pupal stage. African trypanosomiasis is traditionally divided into two types, one prevalent in west and central Africa, where the parasite is *Trypanosoma brucei gambiense*, and the principal vector, *Glossina palpalis*. The other type prevails in east and southern Africa, where the parasite is *T. b. rhodesiense*, and the principal vector, *G. morsitans*.

The number of cases of human African trypanosomiasis reported per year is small compared to that of other major diseases (see Table 4.1). Nevertheless, sleeping sickness is a serious public health problem in Africa because it is usually fatal if untreated. Active surveillance and treatment of cases are the only means of avoiding epidemic outbreaks, but these activities can represent a heavy economic burden. Moreover, the drugs available for treatment vary in their effectiveness and are usually expensive (Cattand, 1993). Experience has shown that tsetse eradication is unrealistic, if not impossible. Currently, vector control aims at minimizing human exposure to fly bites. Advances in this field have benefited from the development of relatively non-toxic pyrethroid pesticides, useful for the impregnation of tsetse-attractive devices, such as traps, targets and screens (Cattand, 1993; Rozendaal, in press).

Historical records of sleeping sickness incidence and of population densities of *G. palpalis* and other tsetse species in Burkina Faso and Côte d'Ivoire, and of tsetse species in Burkina Faso and Senegal, have demonstrated a clear negative correlation between progressive desertification and tsetse abundance, reflecting the tsetse fly's vital dependence on shrub and tree cover (Laveissière, 1976; Laveissière et al., 1985; Laveissière & Hervouët, 1991). Since 1953, and as meteorological conditions in the Sahel have become drier and harsher, the northern boundaries of tsetse distribution have shifted 50–100 km southward. Land-use changes can also affect the suitability of environmental conditions for tsetse survival through their impacts on the temperature:humidity ratio, ultimately leading to changes in patterns of tsetse disease transmission (Cattand, 1995, personal communication).

The geographical distribution of *G. morsitans* has been mapped using climate and vegetation indices obtained through satellite remote sensing, and a correlation between the predicted distribution of the vector and human infection rates of African trypanosomiasis has been found (Rogers & Williams, 1993) (see Box 9.4). In Kenya and Tanzania only a very small difference in mean temperature was observed between areas where *G. morsitans* does and does not occur, thus indicating that a small change in temperature may significantly affect its distribution boundaries (Rogers & Packer, 1993).

Dengue and other arboviruses

Many vector-borne disease agents are viruses. Arboviruses, of which more than 500 have been identified, have arthropod vectors. Over 100 of these can induce disease in humans and around half of them are transmitted by mosquitos (Karabatsos, 1985; Benenson, 1990). Arboviral infections span a wide clinical spectrum, ranging from those that cause mild feverish illness or asymptomatic infection, to those causing severe and often fatal encephalitis or haemorrhagic disease. Under favourable environmental conditions, an arboviral disease can become epidemic from a local endemic base, following its introduction to a previously unaffected area or to a new vertebrate host species. Arboviral infections that would be likely to extend their range as a result of climate change include dengue, yellow fever and the viral encephalitides (Hardy, 1988; Longstreth, 1989).

Dengue

Dengue is widespread in Asia, Oceania, parts of Australia, the Caribbean, tropical America and parts of Africa. It is usually a febrile illness and is caused by one of four distinct dengue virus strains (dengue 1, 2, 3 and 4). Infection with one strain of dengue confers life-long immunity against further infection with that strain, but no heterologous protection against the other strains. Indeed, evidence suggests that second or subsequent infections with other dengue strains are significantly associated with the more severe clinical manifestations, namely, dengue haemorrhagic fever (DHF) and dengue shock syndrome (DSS). Dengue is characterized by the abrupt onset of fever, severe headache, muscle and bone or joint pain ("break-bone fever"), nausea, vomiting and skin rash. DHF is characterized by four major clinical manifestations: high fever, haemorrhagic phenomena, often with concurrent concentration of red blood cells due to plasma leakage, enlargement of the liver and circulatory failure. DHF now ranks as one of the leading causes of hospitalization and mortality of children in south-east Asia (IOM, 1992). DHF can evolve into DSS, a syndrome referring to patients who progress to shock suddenly after 2–7 days of fever (Stevenson, 1987). In the absence of proper clinical management, DSS can be fatal. There is no vaccine or effective specific therapy for any form of dengue.

The vector responsible for major dengue epidemics is the domestic, container-breeding *Ae. aegypti* mosquito. Dengue may also be transmitted by *Ae. albopictus*. The current range of *Ae. aegypti* is limited by cold weather, which kills both larvae and adults. For example, in Australia, its distribution is restricted to areas with a mean mid-winter temperature exceeding 10°C; in the USA its current northern limit is 35°N latitude, corresponding to the 10°C winter isotherm (Shope, 1991). Since *Ae. aegypti* does not survive freezing temperatures, cooler climates have so far limited the persistence of imported dengue in the USA. Moreover, the epidemic transmission of dengue is seldom sustained at temperatures below 20°C (Halstead, 1990).

But elsewhere, particularly in tropical urban centres, dengue epidemics have increased in number and severity. The evolutionary pattern of the disease observed in Asia 20 years ago — from sporadic non-fatal dengue to more regularly occurring outbreaks, with increasing proportions of DHF and DSS — is now being observed in the Americas (Gubler, 1987; Gubler & Trent, 1994). For instance, during the past decade, annual dengue epidemics have started to occur in Central and South America, as they did in Asia about twenty years ago. Although no clear evidence has yet been found of regional climatic influence, the primary vector, *Ae. aegypti*, has reappeared in areas from which it had been eradicated. *Ae. aegypti* has also been reported at above 2200 m in Colombia. Temperature previously limited this species to an altitude of 1500 m in this country (Suarez & Nelson, 1981). In Mexico too, dengue has recently spread to previously unaffected higher altitudes (Herrera-Basto et al., 1992). It therefore seems likely that climate change would affect the distribution, life cycle and population dynamics of this vector.

Several strains of *Ae. aegypti* are well adapted to temperate climates, but most of them prefer tropical or subtropical conditions. The emergence of one generation of *Ae. aegypti* usually takes about 15 days at 27°C. However, a strain captured in a reinfested area near Buenos Aires, has a cycle of only 9 days and, therefore, a potentially higher infestation rate at temperatures of up to 28°C (Carcavallo et al., 1995). According to Koopman et al. (1991), an increase of 3–4°C in average temperature may double the reproduction rate of the dengue virus. A simple mathematical model has estimated a three-fold increase in the incidence of dengue in Indonesia by 2070 in response to a mid-range or "best-estimate" climate change scenario (Asian Development Bank, 1994). However, this prediction is based on limited dengue and climate data.

A population-based epidemiological study in Mexico identified temperature as the key "predictor" of dengue infection (Koopman et al., 1991). Moreover, laboratory studies on incubation periods have indicated that warmer global temperatures could facilitate earlier transmission by accelerating mosquito larval development (Watts, 1987). This would lengthen the season during which epidemics could occur, and extend the vector's range. A national seroprevalence survey undertaken in Mexico in 1986 also pinpointed temperature as a key predictor of dengue transmission (Koopman et al., 1991). The investigators found that median temperature during the rainy season most strongly predicted dengue infection; a four-fold increase in risk of infection was observed between 17°C and 30°C. No seropositive persons were identified in localities where average temperatures during the rainy season fell below 19.3°C. Laboratory studies support the field data (Watts, 1987). The extrinsic incubation period *in vitro* for dengue type 2 was 12 days at 30°C but only 7 days at 32–35°C. Shortening the incubation period by 5 days would result in a potentially three-fold higher reproduction rate (Koopman et al., 1991).

Ae. albopictus, the Asian "tiger" mosquito, is an opportunistic dengue vector. But unlike *Ae. aegypti*, it is able to tolerate cold weather. It transmits not only dengue, but also yellow fever, and several encephalitides. It breeds readily in both urban and rural areas, whereas *Ae. aegypti*, which also transmits both dengue and yellow fever, is more restricted to cities. The mosquito arrived in the USA from Asia in 1985 in a shipment of used tyres and is now found in twenty-four south-eastern US states and as far north as Nebraska and Iowa. *Ae. albopictus* has also reached Mexico, the Caribbean and Brazil and is spreading still further. In 1987 the species was also found in Albania and thereafter in Italy (Knudsen, 1994, 1995). In the USA, the range of *Ae. albopictus* extends 7° further north than that of *Ae. aegypti* because a suspended physiological state, the diapause, enables its eggs to delay hatching and withstand cold temperatures. Meanwhile, by 1994, all four serotypes of dengue had been introduced into the Americas.

If a competent vector species is present, one febrile person would be sufficient to trigger a dengue outbreak in a previously unaffected area. Rapid air transport and increased mobility have rendered such a combination of circumstances far more common than previously. Human migrations and the adaptation of mosquitos, particularly to the domestic human environment, has dispersed both *Ae. aegypti* and *Ae. albopictus* to most intertropical regions of the world and the infection, or the potential risk of infection, has thus been extended to many temperate areas.

Yellow fever

Yellow fever is a general viral infection confined to tropical climate zones outside Asia and the Pacific (where strong measures are taken to prevent its "importation"). In recent years, the majority of cases and deaths have occurred during urban epidemics in west and central Africa. The disease attacks mainly the liver, and has a 20–50% mortality rate. Development of an efficient vaccine has decreased both the number of outbreaks and mortality rates. However, the large quantities of vaccine and efficient delivery system required to deal with massive outbreaks in major urban centres are not always available. Urban yellow fever is transmitted by *Ae. aegypti*, but the urban cycle starts only if the virus is imported from sylvatic animal reservoirs (of monkeys for example) in rural areas, via infected travellers. In these areas, the wild transmission cycle is maintained by *Aedes*, *Haemagogus*, *Mansonia* and *Sabethes* spp.

Climate warming may increase the currently rather low risk of urban epidemics of yellow fever in east Africa and the Americas. Temperature influences the speed with which the virus develops. The extrinsic incubation period of the yellow fever virus thus varies four-fold, from 8–10 days, to several weeks. The survival of the *Aedes* vectors, however, is heavily influenced by human behaviour, particularly the storage of drinking-water in small vessels, which increases risk, and the degree to which control measures are implemented.

Arboviral encephalitides

Arboviral encephalitides are of particular public health concern in temperate countries. In the USA, a large proportion of all reported encephalitis cases is caused by arboviruses. Most cases are mosquito-borne and include, in order of prevalence: St Louis encephalitis (SLE), La Crosse encephalitis, and western and eastern equine encephalitis (WEE and EEE) (Shope, 1980).

The clinical features of infection with the SLE virus range from headache to aseptic meningitis and encephalitis. The case-fatality rate is 20–80% among the elderly. In the USA, SLE epidemics generally occur south of the 20°C June isotherm, but northerly outbreaks have been reported during unseasonably warm years. The potential public health impact of this disease is indicated by epidemic years, such as 1975, when 1815 cases of SLE were reported in the USA (CDC, 1994e).

Box 4.5. Climate change and encephalitis in the USA

Field and laboratory studies have shown that temperature is the most important determining factor with respect to transmission of a viral agent by a vector. The primary mosquito vector of western equine encephalitis (WEE) and St Louis encephalitis (SLE) is *Culex tarsalis*. Laboratory studies indicate that if temperature increases from 10°C to 34°C, the time required for larval development is shortened. However, adult survival decreases with increasing temperature. Every 1°C increase in mean air temperature decreases the probability of daily survival by 1%. But although decreased adult survival would result in decreased population size at temperatures above 30°C, larval development would progress more rapidly and blood-feeding and egg-laying occur earlier in life. Thus the efficiency of virus transmission may actually increase if temperatures rise, due to greater frequency of host contact.

The extrinsic incubation period of the WEE virus decreases as a function of increasing temperature, and more rapidly so than for the SLE virus. The lowest temperature at which virus transmission can occur is 11°C for WEE and 15°C for SLE. At temperatures above 25°C, multiplication of the WEE virus in the mosquito becomes less efficient, reducing vector competence. In California, USA, the horizontal transmission of WEE and SLE viruses is interrupted every winter following the vector's entry into diapause in autumn. The vector re-emerges the following spring. Diapause is triggered by changes in photoperiod and in ambient temperature.

A 5°C temperature differential between two valleys in California, USA, provides a unique natural laboratory in which to study climate change impacts on vectorial capacity. The Coachella and San Joaquin valleys are only 400 km apart, but over a 30-year period the average temperature of the Coachella Valley has been about 5°C higher, during most months, than the temperature of the San Joaquin Valley. In the San Joaquin Valley *Cx. tarsalis* is most abundant in late summer. In the warmer Coachella Valley, *Cx. tarsalis* abundance peaks in both spring and autumn. Although other factors such as the timing and quantity of agricultural irrigation are important, it appears that *Cx. tarsalis* abundance declines if temperatures exceed 28°C.

Results from WEE and SLE transmission dynamics models indicate that if temperature increases to between 25°C and 30°C, the decrease in extrinsic incubation period is more significant for virus transmission, for both WEE and SLE, than the decrease in daily survival. However, an increase from 30°C to 35°C would result in fewer infected blood-feeding mosquitos and reduced virus transmission. Therefore, if temperatures exceed 30°C, virus transmission during summer may be eliminated.

A 3–5°C increase in ambient temperatures may alter the seasonality of vector abundance and arbovirus transmission in California markedly. For example, in south-east California, *Cx. tarsalis* activity could shift from summer to winter; the combined impact of decreasing mosquito–host contact and vector competence could eliminate WEE virus from this area. Conversely, higher temperatures may increase the effectiveness of SLE virus transmission. A 5°C increase in autumn temperature in the San Joaquin Valley could delay the induction of diapause, allowing blood-feeding and virus transmission to continue into the winter months. Such a situation would be similar to the current situation in the warmer Coachella Valley.

Sources: Reeves et al., 1958; Kramer et al., 1983; Reisen et al., 1993; Reeves et al., 1994.

On the basis of field and laboratory studies, Reeves et al. (1994) forecast that a 3–5°C temperature increase will cause a significant northern shift in both WEE and SLE outbreaks in North America (see Box 4.5). WEE may disappear in southern endemic regions and SLE may extend further north into Canada where sporadic outbreaks already occur. However, estimates of the anticipated increase in human cases have not yet been made (Reeves et al., 1994). Human outbreaks of SLE are highly correlated with several-day periods of temperatures exceeding 29°C (Monath & Tsai, 1987). In every endemic area, the rainy season is the epidemic season for both WEE and SLE. Studies on annual temperature cycles are the key to determining whether increased winter temperatures would amplify viral reproduction between seasons (Reisen et al., 1993).

The transmission of eastern equine encephalitis (EEE) and La Crosse encephalitis is linked to the deciduous forest ecosystem which is predicted to undergo northward migration in the USA with climate change. The transmission cycle of EEE is also likely to be affected by an increase in mean seasonal temperatures and increases in brackish water due to sea level rise (Freier, 1993).

In Australia, increased temperature and precipitation would influence the range and intensity of a number of arboviral infections. For example, certain insect vectors and natural vertebrate hosts are likely to spread southwards and proliferate in response to warming and increased precipitation, leading to increases in arboviral infections such as Murray Valley encephalitis and Ross River virus. The former can cause serious brain damage. The latter causes multiple, often long-lasting joint inflammation (Nicholls, 1993; Sutherst, 1993).

Non-viral tick-borne diseases

Ticks transmit several rickettsial and other non-viral pathogens to humans. Since ticks are ectoparasites, their geographical distribution depends primarily upon the distribution of suitable host species, usually mammals or birds. The distribution of ticks is further limited by climatic factors, predators and habitat. Temperatures must be sufficiently high for completion of the tick's life cycle, and low enough in winter to suspend the life cycle, while humidity must be sufficient to prevent tick eggs from drying out. Higher temperatures enhance proliferation of the infectious agent within the tick, although temperatures above the optimum range reduce the survival rate of both ticks and parasites.

In east and south-east USA, Rocky Mountain spotted fever (RMSF) is a widespread rickettsial disease. It belongs to the typhus group of fevers and is caused by *Rickettsia rickettsi*. The vectors are the American shield ticks *Dermacentor albipictus* and *D. venustus*. In a computer simulation model based on direct climate effects, the distribution of the vector diminished in south-east USA under climate scenarios for the region that predict higher temperatures and lower humidity (Longstreth, 1989). RMSF incidence could therefore be anticipated to decrease under these conditions should they occur.

Lyme disease is a non-viral disease caused by *Borrelia burgdorferi*, a spirochaete-like organism, and transmitted by different tick species in temperate zones around the world. Local transmission is often associated with the availability of hosts (deer and deer mice) and vegetation. Recent increases in Lyme disease incidence in north-east USA have been linked to increased human activity, such as habitation and conservation, in forest areas and increased deer populations. Higher temperatures could lead to yet greater incidence since these might enable tick populations to multiply, while at the same time causing a decrease in populations of predators of deer mice.

Onchocerciasis

Onchocerciasis, or river blindness, is a vector-borne disease affecting approximately 17.5 million people in Latin America and west Africa. Most cases occur in west Africa. However, the WHO Onchocerciasis Control Programme has now almost eradicated the disease from eleven African countries by means of chemical vector control and ivermectin treatment.

The principal vectors of onchocerciasis are blackflies of the *Simulium* genus. The infectious agent transmitted during the blood-meal is the infective larva of the *Onchocerca volvulus* parasite. The parasite is a nematode which damages the skin, the lymphatic system, and in the most extreme cases, the eye. Given that the vector depends upon fast-flowing water for successful reproduction, and the adult vector can be spread by wind, climate plays an important role in onchocerciasis incidence (WHO, 1985). This is significant in savanna regions especially, since in these the flow of river water is directly influenced by climate.

A recent simulation study of the potential impact of climate change on blackfly populations in west Africa showed that if temperature and precipitation were to change across areas immediately south of the Sahel, as predicted by a GCM climate change scenario, blackfly populations could increase by as much as 25% at current breeding sites (Hansen et al., 1988; Mills, 1995). The implications of such an increase for the transmission of the disease would depend primarily upon the level of control already achieved and the efficiency of the primary health care system in administering prophylactic drugs. Since the vectors can travel hundreds of kilometres on wind currents, new habitats in previously unsuitable areas could be colonized quickly by blackflies, and the risk of onchocerciasis introduced (Garms, Walsh & Davis, 1979; Walsh, Davis & Garms, 1981; WHO, 1985).

Schistosomiasis

Schistosomiasis is a water-based infectious disease, caused by five species of the trematode *Schistosoma*. Symptoms vary but include bloody urine and liver disorders. Worldwide prevalence has risen since the middle of the 20th century. This may be due largely to the expansion of irrigation systems in hot climates where viable snail populations (the intermediate host) can find human parasite carriers (White, Bradley & White, 1972; Grosse, 1993; Hunter et al., 1993). Waterborne schistosome cercariae penetrate human skin and then infect the blood vessels of the intestines and urinary bladder. Subsequently, the mature parasite's eggs are excreted and often enter surface water (especially canals, ditches and irrigation channels) where they hatch into larval miracidia which can then infect water snails. The parasite multiplies in the snail and one miracidium produces several hundred cercariae, able to infect humans.

Data from both field and laboratory studies indicate that climate change would affect this cycle: temperature influences snail reproduction and growth, schistosome mortality, infectivity and development in the snail, and human–water contact (Martens et al., 1995b). During winter in many countries the water snails tend to lose their schistosome infections. But if temperatures increase, snails may mediate schistosomiasis transmission for a longer period during the year (Gillett, 1974; Schiff et al., 1975; WHO, 1990b). Fluctuations in temperature could also optimize conditions for the several life-cycle stages of the parasite (Hairston, 1973).

Several mathematical models of the transmission dynamics of schistosomiasis are available but usually these are not sufficient for planning control operations. A predictive model of the potential effects of climate change scenarios on schistosomiasis transmission is therefore being developed, similar to the one described for malaria (see page 82) (Martens, 1995). The model indicates that a change in background temperatures may cause the infection to spread beyond current distribution limits. Health impacts may be most pronounced in populations living in less-economically developed temperate areas, where endemicity is low or absent. The model also indicates that the transmission potential will decrease in some areas that are currently endemic because temperatures may become too high for both snail and parasite.

Indirect effects of climate change could also increase incidence of schistosomiasis. Water shortages due to climate change could create greater need for irrigation, particularly in arid regions. If irrigation systems were extended, host snail populations would probably increase, leading to greater risk of infection with the parasite.

Less seriously, but of possible economic impact, several related species of schistosome which are parasitic to mammals and birds, cause cercarial dermatitis ("swimmer's itch") in humans. Incidence of this disease has been rising in Europe and elsewhere due to rising water temperatures, high levels of eutrophication, longer summer seasons and, increased water fowl and mollusc populations (CDC, 1992; Muller, Kimmig & Frank, 1993; Beer & German, 1994; de Gentile et al., in press). Although a "dead end" infection of minor public health importance, it does represent a serious threat to tourism development and its recent increase could be an early sign that climate change is already occurring.

Pest species

Many other organisms — for example, rodents and bats, and pests such as cockroaches — are involved in the transmission of infectious diseases. Information about the potential response of these species to climate and climate change is incomplete, but some of it is outlined below. (Agricultural pests are considered in Chapter 5.)

Rodents

Rodents, whether as intermediate infected hosts or as hosts for arthropod vector such as fleas and ticks, are reservoirs for a number of diseases, including hymenolepiasis and echinococcosis. Their populations are known to fluctuate in response to local and global climate change (see, for example, Slade, Sauo & Glass, 1984; Barreto, Aragon & Epstein, 1995). In a warmer world, rodent populations could be anticipated to increase in temperate zones, resulting in greater interaction between humans and rodents, and a higher risk of disease transmission, particularly in urban areas (Shope, 1991). Indeed, rats are well-known carriers of *Leptospira interrogans*, the agent for leptospirosis or Weil's disease; growing rat populations have increased the risk of human contact with rat urine, increasing the risk of this disease. In some developed countries such as the UK, breakdown in sanitation controls and inadequate hygiene is contributing to growth in rat populations and infestation (Meyer & Shankster, 1994).

In South America, the incidence of rodent-borne arenaviruses which cause haemorrhagic fever ("Junin" in Argentina, "Guaranito" in Venezuela and "Machupo" in Bolivia) has grown. Additionally, a new arenavirus "Sabia" has been discovered in Brazil, but so far, only one natural

Box 4.6. The emergence of hantavirus pulmonary syndrome in the USA

In 1993 in south-western USA, an unusual geographic cluster of deaths from respiratory distress syndrome was observed in a young adult population. The infective agent was found to be a previously unrecognized hantavirus which attacked the lungs; known human infections with hantavirus strains in Asia and Europe primarily involve kidney tissue. More than 124 people in the same area as the cluster have since been diagnosed with hantavirus pulmonary syndrome and nearly half of these cases have been fatal.

Rodents are the primary reservoir for all hantaviruses, transmitting them via their saliva, urine and faeces. The emergence of hantavirus pulmonary syndrome in the USA has been linked to changes in local rodent populations. Changes in land use and climate may have reduced populations of natural predators, while high precipitation following a period of drought increased food availability (in the form of insects and nuts), contributing to a ten-fold increase in the population of deer mouse (the host in the USA) from 1992 to 1993. It has been suggested that human infection occurred because exposure to the virus became much greater following the increase in the density of the deer mouse population.

Sources: Duchin et al., 1994; Wenzel, 1994; Epstein, 1995a.

infection has been reported (Coimbra et al., 1994). In the Americas, shifts in the dominant rodent species and in rodent abundance often occur following forest clearance for agriculture. Meanwhile, in the USA, the emergence of hantavirus pulmonary syndrome has been linked to changes in rodent populations (see Box 4.6).

In cool countries, the rat flea (*Ceratophyllus fasciatus*) does not bite humans, but in warm countries, the Oriental rat flea (*Xenopsylla cheopis*) and the cat flea (*Ctenocephalus felis*) readily bite both rats and humans. This can result in transmission of rat-borne disease organisms, although not necessarily through the biting mouthparts of the flea. Specifically, *Yersinia pestis* (plague) and *Rickettsia mooseri* (murine typhus) are transmitted through flea faeces.

Bats

Haematophagous (blood-feeding) bats of the *Desmodus* species form one of the reservoirs of the rabies virus. Rabies is transmitted when the bat bites either suitable animals or, less frequently, humans, in order to feed. Specifically, *D. rotundus* is found in tropical and subtropical regions of the Americas, its distribution having spread from the central plains of Argentina in the south and from Montevideo, Uruguay in the east, to 26°S (Fornes & Massoia, 1970). This extension in distribution has been due mainly to changes in land use, such as increased cattle production.

Blood-feeding bats are not usually active in winter, but by using sheltered places they are able to tolerate winter temperatures to a certain extent. The higher temperatures anticipated with climate change could affect their feeding patterns by causing them to lose more water and increasing their metabolic rate. This could lead to more frequent blood-meals, and ultimately higher rates of virus transmission.

Flies

Higher mean temperatures and damp winters due to climate change may increase fly (*Musca*) and blowfly (*Calliphora*) populations. Populations of other fly genera may also increase, particularly given the trend towards more intensive animal farming which produces large quantities of manure. All species in these groups are capable of breeding at a temperature of 10°C, and larvae will continue to develop at a temperature as low as 3.5°C. Thus if temperatures rise, contamination of food with enterobacteria or poliomyelitis virus could increase and become prevalent for a greater part of each year. Increased blowfly activity, especially during summer months, could also lead to greater incidence of human cutaneous myiasis. In the UK, recent summers have been warmer than usual and such a pattern has already been observed (Burgess, 1991). Health problems caused by flies can therefore be expected to intensify if temperate zones begin to experience warmer and wetter winters. However, in traditionally warmer parts of the world, higher summer temperatures, combined with drier conditions, would tend to reduce fly breeding success since the insects would have to spend a considerable part of the day sheltering in order to avoid dehydration.

Cockroaches

In common with flies and blowflies, cockroaches (*Blattidae*) are potential "mechanical" carriers of foodborne pathogens and considered to be major hygienic pests of the domestic environment. In temperate climate countries, higher temperatures might encourage cockroaches to venture from the domestic environment and into sewers. Higher temperatures would also facilitate passage of cockroaches and other insects between dwellings, making control of infestations more difficult (Alexander, Newton & Crowe, 1991).

Diseases related to water supply and sanitation

Worldwide, considerable disease is linked to the interrelated problems of water quality, water availability, sanitation and hygiene (see Box 4.7). In developing countries, waterborne diseases such as diarrhoea and those caused by intestinal worms account for 10% of the total burden of disease (World Bank, 1993).

The complex relationships between human health and problems of water quality, availability, sanitation and hygiene are extremely difficult to quantify, however (Kolsky, 1993). For example, there are multiple routes of faecal–oral transmission. Predicting the potential impacts of climate change on water-related diseases is therefore also very difficult. Furthermore, any attempt to do so must take into account water management practices, the growth in demand for water, and a number of other factors not related to climate. Some observations can be made though.

Climate change could have a major impact on water resources and sanitation (see also Chapter 6, pages 129–34) by reducing water supply. This could in turn reduce the water available for drinking and washing, and lower the efficiency of local sewerage systems, leading to increased concentration of pathogenic organisms in raw water supplies. Additionally, water scarcity may necessitate use of poorer quality sources of fresh water, such as rivers, which are often contaminated. All of these factors could result in increased incidence of diarrhoeal diseases. These are caused by a variety of bacteria (e.g. *Salmonella* and *Shigella*), viruses (e.g. rotavirus) and protozoa (e.g. *Giardia lamblia*,

Box 4.7. Water-related diseases

Water-related diseases can be divided into four categories:

- *Faecal–oral diseases*: spread via water or food that is contaminated with faecal material. They include diseases transmitted by direct ingestion of the pathogen and those spread due to lack of water for personal hygiene purposes. Examples include cholera, typhoid, hepatitis A, and diarrhoeal diseases. Diarrhoeal diseases are a major cause of illness and death in young children in developing countries.
- *Strictly water-washed diseases*: spread from one person to another, exacerbated by lack of water for personal hygiene purposes. These include infections of the skin and eye (e.g. scabies, trachoma) and infections carried by lice (e.g. louse-borne epidemic typhus).
- *Water-based diseases:* caused by pathogenic organisms that spend part of their life cycle in aquatic organisms and often associated with standing water. Examples include schistosomiasis, and dracunculiasis. The latter is spread via a minute aquatic crustacean host.
- *Diseases spread by water-related insect vectors:* these vectors breed in water and include mosquitos, which spread malaria, filariasis, dengue and yellow fever, and blackflies, which transmit onchocerciasis, and some species of tsetse fly, which transmit African trypanosomiasis and bite preferentially near water.

Source: Cairncross & Feachem, 1993.

amoebas, cryptospiridium). In southern Africa, where drought conditions have persisted for several years, increased diarrhoeal disease is being observed because populations are now obliged to use contaminated water supplies.

Climate change could also affect water-quality through warming of above-ground piped-water supplies. In parts of Australia, seasonal occurrence of amoebic meningoencephalitis, caused by the *Naegleria fowleri* amoeba, which proliferates in long-distance overland water-pipes in summer, is well documented (NHMRC, 1991). This type of problem would obviously be exacerbated by higher temperatures. Water supplies could also be affected indirectly by salt-water intrusion following sea level rise (see Chapter 7).

Climate change will also affect those aquatic ecosystems such as ponds and wells, and irrigation and drainage systems, that provide breeding grounds for certain parasites or disease vectors. For example, changes in water flow in these systems could influence the incidence of a number of diseases by affecting the residence-time of waterborne pathogens. (For most pathogens, longer residence-times would increase infection.) Natural networks of rivers, lakes and marshes, also play a role in the transmission of water-related and vector-borne diseases. If these undergo increased flooding, following changes in precipitation, community water supplies could become contaminated, leading to greater incidence of faecal–oral diseases.

A climate-induced increase in waterborne and water-washed diseases is most likely to occur within communities that do not have adequate drinking-water supplies and sanitation systems. Developing countries would be at most risk in this respect, and urban communities at greater risk than rural communities. Diarrhoeal disease outbreaks often occur after flooding in such settings.

Climate change might also lead to a decrease in the incidence of some water-related diseases, such as louse-borne diseases which are associated with poor personal hygiene (see also Box 4.7). For instance, epidemic typhus is particularly common in cold mountain areas where clothing is worn for long periods of time. But warming could reduce incidence by reducing the need for warm clothing. Increased availability of water could accelerate such a trend by facilitating improvements in hygiene standards.

Seasonal diarrhoea

Although diarrhoeal diseases affect people of all ages worldwide, the heaviest burden is carried by the young. Diarrhoeal diseases were responsible for around 3 million childhood deaths in the developing world in 1993 (WHO, 1995a). About 80% of these deaths occurred in the first two years of life, mainly due to dehydration. Various etiological agents, such as pathogenic *Escherichia coli*, *Vibrio cholerae* (see next section), salmonellae and several viruses, have been implicated in the causation of diarrhoeal disease. These are transmitted via contaminated food and contaminated drinking-water, and direct person-to-person contact.

It has long been observed that bacterial diarrhoea often peaks during hot and wet seasons, and that this phenomenon is most pronounced in poor, temperate climate countries (Drasar, Tomkins & Feachem, 1981). Until the early part of this century when treatment was greatly improved, "summer diarrhoea" was a major cause of child mortality in England and Wales, and other European countries. Nutritional as well as environmental factors have been postulated to explain the seasonal nature of bacterial diarrhoea (Drasar, Tomkins, & Feachem, 1981). Nutritional factors in mothers relate to early weaning and bottle-feeding, which result in the child concerned being deprived of the protection normally gained from maternal antibodies in breast milk. He or she is therefore exposed to a higher risk of infection. Environmental factors include hot weather, when water becomes scarcer and sanitation poorer, and levels of water and food contamination consequently greater.

In contrast, rotaviral diarrhoeal infection is more common during cool and dry weather. It has been argued that it might be more closely associated with higher rates of interpersonal contact, due to crowding during cool weather, than with decreased survival of the pathogen during hotter episodes (Cutting, 1981). Respiratory transmission is also a possibility.

Some indication of the kind of impact to be expected on seasonal diarrhoea as a result of climate change might be obtainable from an analysis of seasonal fluctuations in diarrhoeal disease incidence, particularly for higher latitudes and altitudes where climatic conditions do not favour year-round transmission. Although the relationships between climate and seasonal diarrhoea are not fully understood, assuming that higher average temperatures would produce a more tropical pattern whereby the distinct seasonality of bacterial and viral diarrhoea would be diminished and the number of cases increased, appears justified. (The effects of seasonal variability on foodborne diarrhoeal and other diseases are discussed on pages 100–101.)

Cholera

Cholera is caused by the bacillus *Vibrio cholerae* and has long been known as a textbook example of a strictly human disease with a faecal–oral transmission pathway. Originally endemic around the Bay of Bengal, it spread to other countries in more or less distinct pandemic episodes. But

Box 4.8. Cholera transmission: a new environmental pathway?

For quite some time *V. cholerae* has been known to be recoverable from wells, water mains, rivers, sea water, and marine crustaceans such as crabs and crayfish. Organic matter and a trace of salt in water (up to 2%) were believed to be necessary for the vibrio's survival. But it was understood not to be able to survive in water for longer than a week, and cholera was accordingly not classified as a water-based disease. The continued survival outside the human host of the "El Tor" biotype, which had lead to local outbreaks only sporadically in the many years prior to its re-emergence in Indonesia in 1961 — which started a pandemic— has been subject to speculation without being resolved. However, non-El Tor vibrios were found in one instance in Japan in an estuary, into which a ditch drained. The vibrios had been breeding in a waste tank used by a hospital for disposal of artificial kidney dialysate.

More recently, an ecosystem-based view of cholera transmission has been receiving increasing attention from scientists. According to this view, the spread of cholera may very often be associated with perturbations of natural ecosystems. Evidence is accumulating that marine phytoplankton provide a refuge for the dormant spore-like vibrio which shelters beneath the mucilaginous sheath of algae. Prolonged survival of vibrios has also been associated with certain diatoms, drifting dinoflagellates, seaweed, macro-algae, water hyacinths and zooplankton. When adverse conditions due to shifts in pH, temperature, salinity and nutrient levels occur, the vibrios contract and "hibernate". Thereafter, when waters warm, the cholera bacillus re-emerges in an infectious state. The spread of cholera may thus be influenced fundamentally by levels of marine eutrophication (caused by discharge of urban effluents consisting of high concentrations of pollutants) and increased sea surface temperatures (a climatic factor), both of which promote the growth of phytoplankton populations. In other words, human-induced and natural disturbances of coastal ecosystems play an important role in cholera transmission.

In Bangladesh, in particular, researchers had long noted the association of fluctuations in cholera with coastal algal blooms, but the environmental reservoir for the vibrio remained a mystery until the non-culturable "hibernating" form was discovered using DNA probes. Furthermore, the appearance and spread of El Tor cholera was of an epidemiological pattern consistent with the role of phytoplankton as an environmental reservoir and amplifier. These recent findings pertaining to a possible new pathway for cholera transmission are becoming widely accepted, although they are still subject to scientific debate.

Sources: Colwell et al., 1985; Stevenson, 1987; Huq, Colwell & Rahman, 1990; Islam, Drasar & Bradley, 1990a, 1990b; Smayda, 1990; Colwell, 1991; Anderson, 1992; Epstein, 1992; Islam, Drasar & Sack, 1993; Islam et al., 1994.

prior to the Seventh Pandemic in 1961, the disease had become steadily more restricted to its endemic centres. In 1961, however, its "El Tor" biotype flared up in Indonesia, spread north and east to Hong Kong, New Guinea, the Philippines, Korea and probably also to China, swept back to south-east Asia, hit India, and the Middle East, and parts of Africa and Europe (Cruickshank, Standard & Russell, 1976). The Eighth Pandemic started to invade sub-Saharan Africa around 1970, spreading to South America in the early 1990s. A new and more virulent strain, *V. cholerae 0139*, is now spreading westward from South Asia into the margins of eastern Europe (Epstein, 1995a).

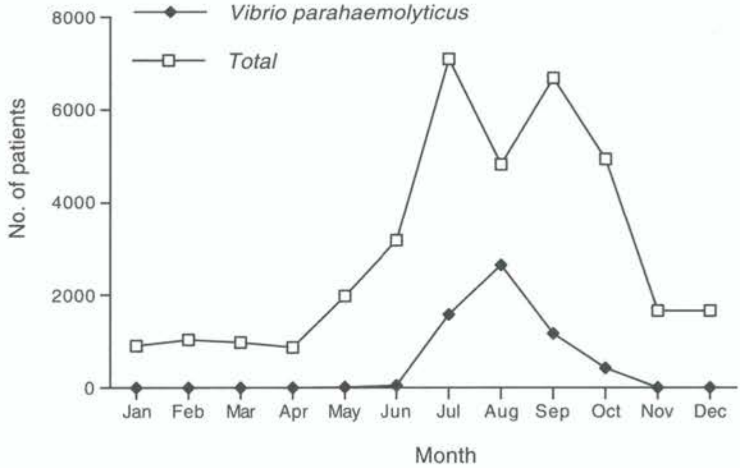
Cholera outbreaks have been associated with precipitation extremes, both droughts and floods. They also often occur during environmental emergencies, such as mass migrations. Cholera outbreaks are particularly common, for instance, in refugee camps. Coastal entry points have traditionally been considered the source of outbreaks since these are the entry points for refugees and other migrants, and also for infected food imports. Moreover, sanitation is often poor in such areas, leading to contamination of local seafood. If these factors are used to construct what would be a relatively simple model of cholera transmission, the various components of climate change, such as rising temperatures, changing precipitation patterns, greater frequency of storms and floods, and sea level rise, could be expected to cause an increase in cholera incidence. Recent findings, however, have changed views on the survival of *V. cholerae* outside the human host and between pandemic episodes. They are also beginning to shed light on some more complex environmental mechanisms that might link the new patterns of epidemic spread and the emergence of new strains to human-induced environmental changes, including oceanic eutrophication and rising sea surface temperatures that favour phytoplankton growth (Islam, Drasar & Sack, 1993). Full assessment of climate change impacts on cholera may therefore require a systems-based approach (see Box 4.8 and Chapter 9).

Foodborne diseases

Up to 70% of all diarrhoeal episodes may be due to ingestion of contaminated food (Esrey & Feachem, 1989). Although food refrigeration is adequate in most developed countries, foodborne disease incidence, particularly diarrhoea, continues to be affected by fluctuations in ambient temperature. In fact, a seasonal trend is often observed regarding foodborne disease incidence. Fig. 4.7 illustrates the seasonal pattern in Japan, where foodborne cases and outbreaks are reported more often during summer months. Since climate change is expected to entail greater variability in seasonal and interseasonal temperatures, foodborne disease incidence may increase.

A study of reported cases of foodborne illness in the UK for the period 1982–1991 found that a clear-cut overall increase in reported cases had occurred, but that more cases had been reported in late summer months than in colder months (Bentham & Langford, 1995). A particularly strong relationship was observed between rates of foodborne illness and temperature in the month preceding the illness (but not between rates of foodborne illness and temperature in the month in which illness occurred). However, this relationship was subject to a threshold effect; below 7.5°C no relationship was observed, but above this temperature the relationship was very strong. This indicates that high ambient temperatures have their most significant impact at points in the UK food system before the food reaches the consumer. Assuming maintenance of the current UK agri-food system, it would appear that food poisoning incidence will rise in the UK during the next half century in response to temperature change. Increases in food-poisoning cases are estimated

Fig. 4.7. Seasonal trends in foodborne illness in Japan in 1994



Source: data from Japanese Ministry of Health and Welfare, 1994.

at between 5% and 20% per month for 2050, with the highest proportional monthly increases predicted to occur in spring and autumn (Bentham & Langford, 1995).

Other factors such as the increasing homogeneity of food systems are also linked to foodborne disease. Agri-food systems, for example, are becoming more and more centralized, due to use of more genetically homogeneous stocks of plants and animals, new technologies such as irradiation, and more efficiently controlled high-volume throughput. Such systems are creating larger and more homogeneous ecological niches for infectious agents. If the effects of ambient temperature do have a significant impact during the pre-consumer steps of the food chain, any changes in background climate would interact with these other factors and promote yet further infection.

Foodborne trematode infections

Foodborne trematode infections are a major public health problem. Worldwide, over 40 million people are affected every year, mainly in south and south-east Asia. Infection occurs after consumption of raw plants, raw or undercooked freshwater fish, or shellfish, that contain parasites at an infective stage. Climate change could affect the incidence of infections directly, via impacts on populations of the snail host, or indirectly, by increasing the need for irrigation dams which, if built in endemic areas, would create additional host reservoirs (Abdussalam, Kaferstein & Mott, 1995).

In particular, incidence of fascioliasis, which is a health hazard for around 180 million people in eight endemic countries, would be affected by climate change. This is because the life cycle and population size of aquatic snails of the genus *Limnaea*, which serve as the intermediate host, are very sensitive to temperature (WHO, 1995d). Human fascioliasis is now endemic in the Nile delta in Egypt and in the Caspian area of Iran, and in both areas its prevalence is associated with high density of snail populations.

Marine organism biotoxins

Acute poisoning following the consumption of fish and shellfish contaminated with biotoxins has been reported throughout the world (WHO, 1984). Around 40 of the 5000 known species of marine phytoplankton can produce potent biotoxins. These commonly enter the food chain via clams and mussels.

Phytoplankton respond rapidly to changes in environmental conditions and are therefore sensitive biological indicators of the combined influences of climate change and environmental change. Algae are an important component of phytoplankton. Proliferation of these algae produces "algal blooms" and is associated with several environmental factors including sunlight, pH, ocean currents, winds, sea surface temperatures, and run-off (which affects nutrient levels) (Valiela, 1984; Epstein, Ford & Colwell, 1993). They have a generation time of hours — compared to zooplankton which have generation times of days, and fish, sea mammals and sea birds, which generation times of months or years. Algal blooms can be harmful to fish and other aquatic life and often cause severe economic damage (Table 4.2) (Epstein, Ford, Colwell, 1993).

Ocean warming could increase phytoplankton population densities in various ways, for example, via increased coastal upwelling and resultant enhanced nutrient supply in the oceans' upper layers. More directly, higher sea surface temperatures could reduce dissolved oxygen levels, which would be harmful to herbivorous species that graze on phytoplankton, thereby enabling phytoplankton populations to grow. It would also enable phytoplankton metabolism and reproduction to increase (Bakun, 1994). The occurrence of harmful algal blooms may be linked to El Niño episodes which are associated with increased sea surface temperatures (see Boxes 2.2 and 4.9). The increased duration, persistence and biological diversity of recent coastal algal blooms and the appearance of novel, noxious species during the past two decades, may be some of the first detectable signs of climate change.

Table 4.2. Types of harmful algal bloom

1. Species which produce basically harmless water discoloration; however, under exceptional conditions, blooms can grow so dense that they can kill fish and invertebrates due to oxygen depletion. Dense blooms may also cover coral reefs and cause "die-off".
2. Species which produce potent toxins that can find their way through the food chain to humans, causing a variety of illnesses:
   - paralytic shellfish poisoning (PSP)
   - diarrhoeic shellfish poisoning (DSP)
   - amnesic shellfish poisoning (ASP)
   - ciguatera poisoning (from reef fish)
   - neurotoxic shellfish poisoning (NSP)
   - cyanobacterial toxin poisoning
3. Species which are non-toxic to humans, but harmful to fish and invertebrates, especially in conditions of intensive aquaculture, by damaging or clogging gills.
4. Species which harbour and amplify *Vibrio cholerae* and other bacteria that cause gastroenteritis.

Source: Hallegraeff, 1993.

Box 4.9. El Niño/Southern Oscillation and impacts on disease

The El Niño/Southern Oscillation (ENSO) is a pattern of climate variability that directly affects countries bordering the Pacific and Indian Oceans (see Chapter 2). Weather events around the world are also "teleconnected" to the ENSO phenomenon. Climate models indicate that global warming may interact with ENSO events and increase anomalous weather patterns. ENSO episodes amplify normal climate variability and affect the frequency of climatic extremes such as drought and excessive precipitation. The following examples involving ENSO events illustrate that, for some diseases, changes in climate variability associated with climate change may be more important than changes in mean climate.

The occurrence of harmful algal blooms may be linked to El Niño episodes which are associated with ocean warming and could increase in number or magnitude following climate change. The more frequent red tides observed along the US north-east coast and the Far East, which coincided with recent ENSO events, may be an example of such a link. (Red tides indicate organic pollution and that temperatures of ocean surface waters are high.) Indeed, the ocean warming associated with the 1986–1987 El Niño event appears to have supported new growths of phytoplankton species at higher northern and southern latitudes. More specifically, in 1987, the *Gymnodynium breve* dinoflagellate, the agent of neurotoxic shellfish poisoning, formerly found in the Gulf of Mexico, bloomed off North Carolina, USA, following atypical weather and shifts in ocean circulation patterns.

Incidence of vector-borne diseases is often associated with the occurrence of climatic extremes such as excessive precipitation. In temperate south-east Australia, infrequent but severe epidemics of Murray Valley encephalitis (which can cause serious brain damage) occur after extended precipitation and flooding; heavy precipitation causes a rapid increase in the population of the mosquito vector. Many outbreaks correlate with ENSO phenomena. The Southern Oscillation index, one of the ENSO parameters, which relates to air pressure deviation, can be used to predict the probability of an epidemic. Other vector-borne diseases for which a strong association between outbreaks and El Niño years has been observed include: eastern equine encephalitis in north-east USA, epidemic polyarthritis caused by the Ross River virus in Australia, and malaria.

Many areas across the globe that are affected by malaria experience drought or excessive rain coincident with ENSO teleconnections. Quantitative leaps in malaria incidence in Costa Rica and Pakistan, for instance, are coincident with ENSO events. Historically, in the Punjab region of north-east Pakistan the risk of a malaria epidemic increases 5-fold during the year following an El Niño year and in Sri Lanka the risk of a malaria epidemic increases 4-fold during an El Niño year. These increased risks are associated with above-average levels of precipitation in the Punjab and below average levels of precipitation in Sri Lanka.

Sources: Nicholls, 1986; Kiladis & Diaz, 1989; Glantz, Katz & Nicholls, 1991; Edman, Timperi & Werner, 1993; Hallegraeff, 1993; Nicholls, 1993; Bouma, Sondorp & van der Kaay, 1994b; Kerr, 1994; Tester, 1994; Bouma, 1995.

Two main types of biotoxin poisoning are associated with temperate climates and colder coastal waters: paralytic shellfish poisoning and diarrhoeic shellfish poisoning. If water temperatures rise due to climate change, shifts in the distribution and significance of these diseases could occur. At the same time, biotoxins associated with warmer waters, such as ciguatera in tropical waters, could extend their range to higher latitudes (Tester, 1994). Already, in New Zealand, an increase in coastal temperatures has enabled toxin-related organisms to establish themselves in new areas (Epstein & Jenkinson, 1993). Ocean warming has also been observed to cause shifts in plankton populations, with the result that the smaller species (pico-phytoplankton), which contain the more toxic dinoflagellates and cyanobacteria, become predominant (Valiela, 1984). However, because the relationship between phytoplankton and temperature is poorly understood, predicting the future impact of climate change on algal blooms is difficult.

Evidence also suggests that changes in the marine environment are leading to the emergence of diseases in places in which they had not been observed previously. For instance, domoic acid, which is a toxin produced by the *Nitzschia pungens* diatom and which causes amnesic shellfish poisoning, appeared on Prince Edward Island, Canada, for the first time, in 1987. This was an El Niño year, when warm eddies of the Gulf Stream came close to shore and heavy rains increased run-off (Hallegraeff, 1993).

Person-to-person infections

Meningococcal meningitis

Changes in temperature and humidity may affect person-to-person infections since transmission of the infective agent involved often increases during cold spells due to crowding, while at the same time dust and dry air may render mucous membranes more susceptible to infection. A typical example of such an infectious disease is meningococcal meningitis, caused by *Neisseria meningitidis*, serogroup A, which causes severe seasonal epidemics in the so-called "cerebrospinal meningitis (CSM) belt" in the Sahelian part of Africa (Cvjetanovic, 1976). These epidemics appear to be a reflection of changes in the case:carrier ratio, the numbers of carriers remaining almost constant over time (Greenwood et al., 1984). Based on the analysis of one longitudinal study in Burkina Faso and another in Nigeria, Greenwood et al. (1984) postulate that dry air and overcrowding in winter may predispose individuals to systemic meningococcal infection rather than to being carriers. In the Nigerian study (covering 1977–1979), peak clinical meningitis incidence was strongly correlated with the highest maximum mean temperature of the (winter) season and inversely correlated with absolute humidity to a lesser, although still significant, extent. This suggested that atmospheric conditions determine efficacy and dosage of airborne transmission.

Since the early 1980s, meningococcal disease epidemics have occurred throughout the CSM belt, in Benin, Burkina Faso, Chad, Gambia, Ghana, Mali, Niger, Nigeria, Senegal and Togo, culminating in severe epidemics in Ethiopia and Sudan during 1987–1989. More than 30 000 cases were reported in Sudan in 1988, the year of peak incidence, and over 40 000 cases in Ethiopia in 1989 (WHO, unpublished data). During the same period, meningococcal disease epidemics occurred in other African countries. The epidemics seen towards the end of the 1980s and the early 1990s in Burundi, the Central African Republic, Kenya, Rwanda, Tanzania, Uganda and Zambia, illustrate the spread of the disease beyond its usual boundaries. Such epidemics may represent a truly new feature in the epidemiology of meningococcal disease. Their cause could be extension of drought areas due to climate change, or increased mobility of the population whether by voluntary travel, or through warfare and subsequent refugee movement. The introduction of a new meningococcal strain into susceptible populations is another possible cause.

Meningococcal disease epidemics take place in the same period of the year as the seasonal upsurge in cold and dust observed in non-epidemic conditions: in winter and spring in temperate countries, and in the dry season in tropical countries (WHO & Fondation Marcel Merieux, 1995).

Future infectious disease patterns and public health responses

Available evidence and climate change models indicate that climate change will alter the pattern of the world's infectious diseases. But it is not yet possible to predict with certainty or precision how this pattern might change. Admittedly, the accuracy of predictive models for vector-borne diseases such as malaria and dengue, and for schistosomiasis, concur in forecasting increases in the range and sensitivity to climate of these diseases, especially at and just beyond the boundaries of currently endemic areas. However, the predictions are for broad ranges of plausible change — such as 5–10% increases in the numbers of malaria-infected persons and 15–30% increases in the population exposed to potential malaria transmission — in response to a doubling of carbon dioxide levels. These predictive models will be improved though. In the meantime, the lesson to be learned is that the responses of sensitive microorganisms, their vectors and their intermediate (non-human) hosts would be significant, even if changes in climate were modest in scale.

Public health programmes would therefore do well to anticipate the health impacts of climate change on infectious disease. For example, surveillance systems could be improved in sensitive geographic areas. Such areas include those bordering areas of current distribution of vector-borne diseases, and which could themselves experience epidemics under certain climatic conditions. Vaccination programmes could be intensified, and pesticides for vector control and drugs for prophylaxis and treatment stockpiled. Even more importantly, intersectoral collaboration could be strengthened so that public health considerations are incorporated into the development process via environmental management techniques. More specifically, the health sector could, in some areas, use information from regional climate forecasts in its programmes, enabling more proactive health care planning.

Throughout history, human health has been closely associated with social and environmental factors. In a world in which climate change coexists with an array of mounting social and environmental stresses, we should expect that new synergies between environmental quality, the biology of infectious diseases and human health will challenge the delivery of health care.

Chapter 5

Climate, food production and nutrition

World food supplies

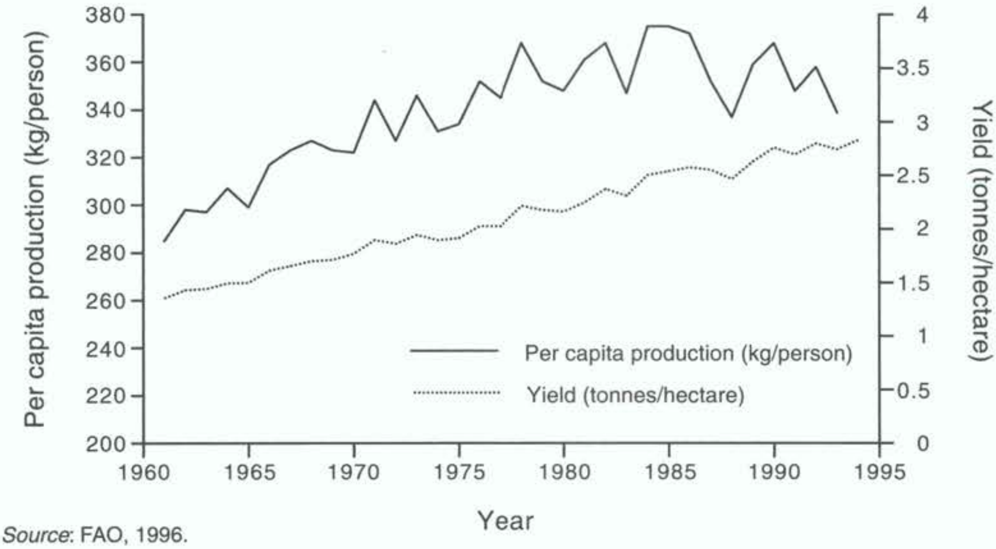
Human metabolic-energy requirements are lower in warmer climates than in colder climates and nutritional requirements accordingly lower too. Human energy requirements can thus be correlated with latitude: requirements are lowest in hot humid climates and highest in cold dry climates. It should be noted, however, that cultural factors, including clothing and behavioural patterns, and technologies that control the thermal environment inside buildings, have served to reduce some of these differences in nutritional requirements. Human food-energy requirements would therefore not be reduced significantly by several degrees of global warming.

Whatever the climate, though, reliable sources of good-quality food are crucial for normal growth and to maintain health. Currently, 700 million people do not have access to sufficient food to meet their needs for a healthy and productive life (Pinstrup-Anderson, 1994). In particular, malnutrition continues to be a major cause of infant mortality, and of physical and intellectual stunting in childhood. Malnutrition also damages the immune system, thereby increasing susceptibility to infectious diseases (Tomkins, 1986). Malnutrition and resulting deficiencies in immune system function may even facilitate the evolution of benign viruses into pathogens (Beck et al., 1995).

Yet during the past 10 000 years of the current Holocene period — which have been relatively stable in climatic terms — farming methods have been evolving and improving, enabling more food to be produced. Most local climatic limitations on crop growth have been overcome through irrigation, fertilization, mechanization, and the breeding of varieties adapted to local conditions. In fact, during the past fifty years, the food requirements of a rapidly expanding population, combined with the worldwide shortage of new tracts of arable land, have placed an unprecedented reliance on yield improvement (Meadows et al., 1992). Many calculations demonstrate, however, that sustaining a population of 10 billion on Westernized diets, while at the same time maintaining ecologically sustainable food production systems, will not be possible using current resources and technology. Moreover, maldistribution of the world's food, which has long been a major cause of local hunger, shows little sign of resolution, adding further complexity to the problem of how to feed the world's burgeoning population (Sen, 1993; Kates & Chen, 1994).

Concern about world food production has increased since the mid-1980s when world per capita production for several major food categories, especially cereal grains, appeared to reach a plateau (Fig. 5.1) (FAO, 1996). Cereal grains account, directly and via livestock feeding, for around two-thirds of world food energy. This recent slow-down in cereal production may have been triggered by the diversion of cereal-producing land into other activities, as has occurred in North and South America, and the depressive effect of falling commodity prices (Dyson, 1994). However, mismanagement of much of the world's agricultural and pastoral land, and consequent impairment of its productive capacity, may have been even more significant factors. Worldwide, inappropriate agricultural practices may account for one-third of Earth's degraded soils. Currently, an estimated

Fig. 5.1. Time trends, 1960–1994, in global yield of cereal grains (tonnes per hectare) and in global production per capita (kg/person)



Source: FAO, 1996.

one-tenth of the world's vegetated surface (1.2 billion hectares) is moderately degraded and 9 million hectares extremely degraded due to a combination of erosion, desiccation, nutrient depletion, and irrigation-induced water-logging and salinization. In Africa, overgrazing by livestock accounts for nearly half of all land degradation (World Resources Institute/UNEP/UNDP/World Bank, 1996).

The optimistic view is that such losses may be offset in the foreseeable future by cultivation of potentially arable land, and genetic engineering of increased disease resistance and yield in plants and livestock (Smil, 1994; Crosson, 1995; Islam, 1995). Furthermore, some of the capacity of the world's food-producing system is underused and were this to be rectified, total food production could be increased. Other gains in world food production could also be realized through large-scale aquaculture, the extension of water-efficient irrigation systems in arid zones, and intensification of fish farming. Reducing food wastage and adoption of diets that contain less meat could also increase global food availability.

The pessimistic view is that in light of current nutritional inequalities worldwide, and increasing dependence on food aid programmes in parts of Africa, it is unlikely that improved agricultural efficiency or the introduction of novel technologies will suffice to ensure adequate diets for the world's population in the longer term (King & Elliott, 1993). Increases in agricultural yields due to selective breeding, fertilizer use and irrigation already appear to be slowing. Confidence that irrigated agriculture can continue to be developed may even be misplaced given the depletion of freshwater aquifers in many parts of India, northern China and the American western plains, and growing competition for fresh water from sectors other than agriculture. Moreover, not only does land degradation continue to be widespread but supplies of readily cultivable virgin land are running out (Buttel, 1990; Meadows et al., 1992). Per-person production of cereal grains may well continue to decline for several decades (Kendall & Pimentel, 1994).

The world's fisheries also appear to be at the limit of their sustainable yield (approximately 100 million tonnes per year) (FAO, 1994). Some fishing grounds, including the once bountiful Grand Banks cod fishery in the north-west Atlantic, have collapsed or have been seriously damaged by prolonged overfishing. In other parts of the world, such as the North Sea, strict, internationally agreed quota have had to be enforced to avoid exhaustion of fish stocks. Fish farming, both at sea and in freshwater systems on land, holds some promise for greater fish production, although current price levels render this method economically unattractive in relation to all but a few fish species.

It is against this uncertain background that regionally diverse, often adverse, climate change impacts upon food production could occur. Long-term changes in global and regional climate would affect some aspects of crop, livestock and fisheries productivity significantly (Ruttan, Bell & Clark, 1994). Climate change could influence food production adversely via:

- geographic shifts and yield changes in agriculture;
- reduction in the quantity of water available for irrigation;
- loss of land through sea level rise and associated salinization (see also Chapter 7);
- impacts upon fisheries productivity through sea level rise, and changes in water temperatures, currents, freshwater flows and nutrient circulation.

Food production could also be affected by the adverse effects of increased ultraviolet radiation (UVR) on photosynthesis, following stratospheric ozone depletion (see Chapter 8). However, higher temperatures, more efficient use of water by plants (caused by an anti-transpiratory effect of carbon dioxide (CO_2)) and CO_2 "fertilization" might increase yields in some areas. But in areas where populations are already barely food-sufficient, even the slightest decline in yields could be very harmful. For instance, climate-related declines in fish catches could pose particular nutritional stresses on human populations in less developed countries, for whom a high proportion of dietary protein is derived from seafood.

The political implications of climate change must also be considered. For instance, land areas suitable for cultivation of key staple crops, or productive fishing grounds, could undergo geographic shifts in response to climate change and become the subject of political conflict, leading to further reductions in food production in some regions.

Impacts of climate change on food production

Predicting the impacts of climate change upon crop and livestock yields is a complex modelling task. Agricultural production is sensitive to the direct effects of climate upon temperature, water flow, atmospheric composition (especially regarding CO_2 levels) and extreme weather events. It is also sensitive to the indirect effects of climate on soil quality, the incidence of plant diseases, and on weed and insect (including pest) populations. In particular, irrigated agriculture would be affected by changes in the rate of replenishment of freshwater aquifers. Assessments made by different scientists of the impact of climate change upon agricultural productivity therefore vary and are beset by great uncertainty (Reilly, 1994; Reilly et al., 1996).

To ensure maximum accuracy, any modelling of the impacts of climate change on agricultural productivity must be integrated — that is, it must encompass climate change scenarios, crop yield responses, patterns of land use, and food distribution pathways (Parry & Rosenzweig, 1993;

Alcamo et al., 1994a, 1994b). Apart from climate factors, productivity trends in the agricultural sector are strongly influenced by changes in national and international market forces, government policies, trade agreements, the development of new strains of crops and the availability of new technologies. Therefore the impacts of global environmental changes on agriculture would be greatly modified by the sector's own internal dynamics (FAO, 1995; in press). In general, the modelling exercises reported to date have not attempted to incorporate social and economic responses. Certainly, human societies would not remain passive in the face of significant changes in food supplies. But in order to "scope" the potential problem, the impact of climate change *per se* must be modelled before attempting to incorporate any social adaptive response. Besides, the complex political, economic and technological influences upon world food production would defy ready quantitative analysis. These influences include those rapid commercial and political changes that have encouraged the production of standardized crops for unseen, remote markets using large-scale, heavily mechanized agricultural production methods, to the extent that food has gradually become an international commodity rather than a source of nutrition for local populations (McMichael, 1994).

Impacts of climate change on crop food production

Temperature, precipitation and carbon dioxide levels

Increased levels of atmospheric CO_2 are predicted to cause global warming, which in turn, would alter regional surface temperatures and affect crop growth. It is already known, for example, that the accelerated maturation of wheat under higher temperatures reduces the growing time for wheat grains — and therefore their final size. More specifically, Australian scientists simulated the *combined* effect of a 3°C increase in temperature, increased CO_2 (to 560 ppmv by 2050), and altered variability in precipitation and soil moisture. They concluded that although the yield of late-maturing strains would be increased, the yield of some early-maturing strains would be halved (Wang, Handoko & Rimmington, 1993).

Increased atmospheric CO_2 would have a fertilization effect (Idso, 1990; Bazzaz & Fajer, 1992; Korner, 1993). But it is unclear how observations of this effect that have been made in experimental conditions would apply in the more complex field situation, and whether the effect is temperature-dependent (Horie, 1993; Vloedbeld & Leemans, 1993). More certainly, increased atmospheric CO_2 would result in partial closure of leaf stomata, reducing water requirements for evapotranspiration in many plant species.

There are two major types of plant: the C_3 plants (such as wheat, soybeans, rice and potatoes) and the C_4 plants (such as millet, sorghum and maize). CO_2 fertilization would affect them in different ways. The C_3 plants include most of today's high-volume crops and evolved aeons ago when atmospheric CO_2 concentrations were higher. They would therefore "welcome" an increase in atmospheric CO_2. The more-recently evolved C_4 plants, which include sugar cane and many weeds, already function near-optimally at today's lower CO_2 levels and their production would therefore increase much less in a CO_2-enriched atmosphere. Over two decades ago, experiments by Akita and Tanaka (1973) demonstrated that high CO_2 concentrations (1000–2500 ppmv) increased C_3 plant growth substantially. Likewise, Imai, Coleman and Yanagisawa (1985) showed that elevated CO_2 (700 ppmv) increased the yield of rice, a C_3 plant. However, C_4 plants were less responsive (Akita & Moss, 1972).

Crop yields are also sensitive to changes in soil moisture. Overall, climate models predict a global increase in precipitation (mostly as greater rainfall intensity — i.e. more rain per rain-day) (Gordon et al., 1993). But although equatorial monsoon rains may extend to higher-latitude regions in Africa's Sahel and in north-west India, and alleviate some drought conditions, intensified precipitation would exacerbate flooding and soil erosion, resulting in destruction of crops and loss of arable land. Elsewhere, in some tropical and mid-continental regions, precipitation may be reduced. Seasonal shifts in annual precipitation patterns could also occur, affecting soil moisture during the growing season, and possibly impairing the growth of many crops. It has been argued that the inherent limitations of plant physiology render longer-term adaptations to a continuing change in climate unlikely (Woodward, 1987).

Climate change could also affect agriculture by causing long-term changes in agro-ecosystems through increased frequency and severity of extreme weather events, such as heat waves, droughts, flooding and cyclones, all of which could exacerbate soil erosion and affect patterns of plant disease and pest infestation. The existing climate scenarios are not sufficiently precise with respect to these climate phenomena, so more detailed predictions cannot be made. The agricultural sector should therefore expect some "surprises".

Overall assessment of the direct effects of climate change on crop production

The Intergovernmental Panel on Climate Change remains cautious about projecting the overall impact of climate change upon world agricultural production. However, there is some agreement that aggregate effects are likely to be adverse, but modest in scale (Reilly et al., 1996). It is more certain that negative impacts would occur in tropical regions. This is unfortunate since many large populations in these regions already suffer from malnutrition. Low-latitude, low-income populations in semi-arid and arid regions who depend on rainfed, non-irrigated agriculture would be particularly vulnerable. There are many such populations in sub-Saharan Africa, south Asia, east Asia, south-east Asia, and on some Pacific islands.

Most of the predictions concerning increases in agricultural productivity that are described above refer to the coming century. Impacts assessments that rely on inputs from transient climate change experiments are better able to model the likely impacts on agricultural productivity over the next few decades and also usually incorporate more realistic forecasts of climate change than those which rely upon the equilibrium experiments of doubled-CO_2 climates (see also Chapter 2). Furthermore, none of the projections described allow for changes in the distribution of insects and weeds, and plant disease incidence.

Indirect effects of climate change on crop productivity: pests and diseases

Plant pests and plant disease vectors are often arthropods, and their geographical distribution is therefore determined by temperature as well as the availability of host plants (see Chapter 4). Some agricultural pests, such as aphids, are favoured by dry conditions, although others, including locusts, proliferate in wet conditions. But all insect herbivores, fungi, bacteria, plant viruses and their vectors, function within certain ecological limits, and can be expected to be affected by climate change.

Many plant pests are highly mobile, have high population growth rates and, since they are sensitive to climate, are likely to respond quickly to climate change (Sutherst, 1991). (Both generic and species-specific mathematical models have been developed to estimate pest response to climate

Table 5.1. Examples of agricultural pests

Pest/Disease	Vector	Agent	Bioclimatic thresholds	Region affected
Dutch elm disease	*Scolytus scolytus* *Hylurgopinus rufipes* (beetles)	*Ceratocystis ulmi* (fungus)	humid	USA, Europe
Whitefly*	*Bemisia tabaci*	Bean golden mosaic geminivirus (BGMV) Tomato virus Cotton virus	hot, dry	West USA Central America
Citrus canker		*Xanthomonas campestri pv. citri* (bacteria)	20–35°C, optimum 30°C	
Aphid* *Toxoptera citricida*		Tristesa virus	hot, dry	Americas
Oriental fruitfly	*Dacusstrumeta dosalis*		14–32°C over 3 months	South-east Asia, India
Citrus blackfly*	*Aleuroconthus woglumi*		>13.7°C, optimum 27°C	Central America, Asia
Japanese beetle *Papilla japonica*			soil temperature 17.5–27.5°C	North-east USA, Japan China
Date palm scale* *Parlatoria blanchardi*			hot, dry	North Africa Middle East
Gypsy moth *Lymantria dispar*			14–21°C	Americas
Whitefringed beetle *Graphognathus* spp.			20–30°C, humid	Africa, USA, Australia
Fire ant, *Solenopsis* spp.			humid, warm	South-east USA
Locust*			hot, dry	Africa

* Homoptera: commonest class of herbivores and plant viral vectors.
Source: Dahlstein & Garcia, 1989.

change; see, for example, Sutherst, 1991.) In general terms, the areas of distribution and population densities of tropical and subtropical pests can be anticipated to expand if temperatures rise (Kiritari, 1988). Crop growth and yield would then be reduced because the generation time of pests would be shorter, and their breeding seasons longer.

Several studies have been undertaken on the potential effect of climate change on pest distribution. Thus it is predicted that in Japan, various crop pests — including the tobacco cutworm *(Spodoptera litura)*, rice stink bug *(Lagynotomus eleongatus)*, lima-bean pod borer (*Etiella zinckenella*), soybean stem gall (*Asphondylia* sp.), rice weevil (*Sitophilus oryzae*) and soybean pod borer (*Leguminivora glycinivorella*) — would probably expand their distribution areas northwards (Mochida, 1991). The distribution area of others — such as the rice leaf beetle (*Oulema oryzae*) and the rice leaf miner (*Agromyza oryzae*) — would contract, however. Farrow (1991) has calculated that in Australia, warming would enable many pest species to extend their overwintering areas southwards, in some cases enabling the pest to invade the whole of their host plants' range. In Table 5.1, some agricultural pests whose distributions may be affected by climate change, their bioclimatic thresholds and optimal conditions, and the areas affected by that pest in the 1980s, are described.

The future severity and frequency of pest outbreaks (e.g. locusts) could also be affected by changes in the frequency of extreme weather events, some of which are related to the El Niño/Southern Oscillation (ENSO) phenomenon (Farrow, 1991). For example, the brown plant hopper (*Nilaparvata lugans*), a rice pest endemic in south-east Asia, is transported annually to Japan and Korea by the monsoon winds. Any shifts in the timing and location of these winds associated with ENSO events would have a significant effect on the extent of rice crop damage (Walker, 1994).

An increase in the frequency of extreme events such as prolonged drought or intense flooding, could create conditions that are conducive to disease or pest outbreaks, and severely disrupt the predator–prey relationships that normally restrict the proliferation of pests. An example of the emergence of an agricultural pest related to climate variability comes from Zimbabwe, where major rodent infestations occurred in 1974–76, 1983–85 and 1994 — a pattern consistent with El Niño years (Epstein & Chikwenhere, 1994a). For example, after six years of drought, the heavy rains of 1992–1993 and the short rains of 1993–1994 created conditions that favoured rapid proliferation of rodent populations. The rodents consumed stored and growing grain alike in 1994. Their populations were able to multiply since the drought had caused a significant decline in populations of both predators and draft animals. (Ploughing normally destroys the rodents' burrows.) This particular example illustrates that the cumulative effects of interannual variability of weather on the dynamics of ecological relationships (see Chapter 9) must be incorporated, with appropriate timelags, when modelling the impacts of climate variability on pests and pathogens.

Pest infestation may also be influenced by increases in atmospheric CO_2, although precise details are lacking (Rosenzweig et al., 1992). Some experiments suggest that insect populations would decline because of the lower nutritional quality of leaves. However, other experiments show that insects would simply consume more leaves to compensate for lower nutritional quality (thereby negating any CO_2 fertilization effects on plant growth) (Bazzaz & Fajer, 1992).

Additionally, climate-related changes in ecosystems could result in the emergence of new types and combinations of pests and diseases. Other factors, such as loss of biodiversity, including the loss of natural predators of plant pests, and overuse of pesticides, could contribute to plant disease outbreaks too. Obviously, the impact of pests on food production following climate change would, to a certain extent, vary according to the local availability and long-term effectiveness of technological defences and adaptations.

Some estimates have been made of the crop losses that could arise if pest, pathogen and weed populations increased following temperature increases. For example, Pimentel et al. (1992) have calculated that a 2°C rise in global mean temperature would cause a 30% decline in crop yields due to greater incidence of plant diseases in what would be a drier North America, and a decline of more than double this figure for some crops in Africa, which could become warmer and wetter. Additionally, intensified competition from weeds could mean that US crop losses rise by a further estimated 5–50% (depending on the crop) since weeds are better adapted to arid conditions than crops.

Warmer and more humid conditions would also enhance the growth of bacteria and mould on many types of stored food, and would increase food spoilage. This could create some specific toxicological health hazards. For example, the tropical-climate food mould, *Apergillus flavus*, which produces aflatoxin (a probable cause of human liver cancer) proliferates in organic matter including crops, such as peanuts, if these are stored in humid conditions (FAO, 1979).

Models and predictions

The net effect of climate-related changes on world food production, and therefore on food availability and nutritional health, remains contentious. Fully-integrated models with the capacity to undertake a multi-stress analysis of agricultural systems are not yet available. For example, predictive models currently do not have the capacity to take into account potential climate-related increases in plant disease incidence and plant damage caused by pests. Limited analyses have been carried out, however, particularly concerning the effect of climate change upon cereal grain production (which accounts for around 70% of world food energy). Two such analyses predict marked regional differences in impact, with high-latitude regions in the northern hemisphere generally benefiting (although not evenly) from climate change as a result of longer growing periods, and most other regions either changing little, or declining in productivity (Leemans & Solomon, 1993; Parry & Rosenzweig, 1993; Solomon et al., 1993). Mid-latitude, mid-continent, summer dryness would also probably occur, particularly in the northern hemisphere. Thus northern Europe and south-central Canada would be more likely to show some gains, and the USA and southern Europe some losses. Elsewhere, drying due to decreases in seasonal rainfall — for instance in semi-arid regions such as sub-Saharan Africa — could have serious negative impacts on crop production.

Some crops — for example, wheat and maize, which are temperate crops — may be subject to substantial declines in yield in their current locations, but might gain considerably in terms of geographic range. Tropical crops, including rice, millet and sugar cane, may not undergo such significant change (Leemans & Solomon, 1993). Further examples of the anticipated impacts of climate change upon agricultural production can be found in Box 5.1.

The results of a recent analysis suggest that a doubling in atmospheric CO_2 concentration (by around 2060) would, via climatic impact alone, cause declines in wheat yield of between 15% and 25% in developed countries, and between 40% and 60% in developing countries (including India, Pakistan, Brazil, Uruguay, and Egypt) (see Box 5.2). However, when allowance was made for a CO_2 fertilization effect, the extent of these estimated declines was reduced by approximately 20%; in fact, some countries such as Australia, Canada and China, and northern Europe, showed increases in yield (Rosenzweig et al., 1993). Studies of local impacts that exclude CO_2 fertilization predict more significant adverse effects.

Such analyses indicate that the quantitative predictions of climate impacts upon crop production depend very much upon which GCM-based climate change experiment is used. The study outlined in Box 5.2, used three GCM climate change scenarios (GISS, GFDL and UKMO) and took into account a CO_2 fertilization effect. It forecast downturns of 1–7% per cent in world cereal grain production by the middle of the next century (Parry & Rosenzweig, 1993). The projected downturns were greatest in low-latitude countries. Another study projected changes in rice production in south and south-east Asia using the same three GCM scenarios ranging from -3% to +28% in India, from -14% to +14% in the Philippines, and from +2% to +27% in Malaysia (Reilly et al., 1996).

Box 5.1. Examples of predicted regional impacts of climate change on agriculture

- Research undertaken in Quebec, Canada, indicates that under the GISS climate change scenario, yields of corn, soybeans, potatoes, beans and sorghum would increase, and yields of cereal and oilseed (i.e. wheat, barley, oats, sunflower and rapeseed) would decrease.
- Modelled estimates for grain maize, sunflower and soybean production in the European Communities, using a scenario from an equilibrium climate change experiment, indicate a northward shift of 700–1900 km in the geographic range of these crops.
- Results based on several GCM equilibrium climate change experiments, indicate that agricultural production in northern areas of European Russia and Siberia may increase, and that the crop zone in this area will shift northward. Predictions based on palaeoclimatic analogues also suggest — especially when the effect of carbon dioxide (CO_2) fertilization is taken into account — that crop productivity in Russia will rise significantly if atmospheric CO_2 levels double. However, under some climate change scenarios, CO_2 fertilization, increased tropospheric ozone, and loss of soil organic matter, are predicted to decrease crop yields by an estimated 10%.
- In the UK, higher temperatures would cause a decrease in cereal crop yields and an increase in the yields of crops such as potatoes and sugar beet, and of forest plantations. Animal production in the north would improve, but might require considerable additional investment in infrastructure. Maize and sunflower might be grown for their mature grain yield as well as for fodder. (Currently, in northern UK, maize cannot be grown for grain production and sunflowers cannot be grown for seed production.)
- It has been estimated that in Senegal, under current precipitation patterns, warming of 4°C would reduce crop yields by 30% by the middle of the next century, depriving 1–2 million people of their source of domestically-produced cereals. In Zimbabwe, warming of 2°C would mean that yields that are currently attained in 7 out of 10 years would be attained in only 2 to 4 out of 10 years. In Kenya, climate change could increase total potential national agricultural production, but exacerbate food shortages in semi-arid areas. Analysis of current crop yields, and potential crop yields following changes in temperature, moisture, CO_2, pest populations and UV-B levels, suggests that a 10% increase in precipitation in Africa would improve crop yields on that continent to a limited extent.
- In New Zealand, higher temperatures could result in substantial shifts in agricultural potential, with the result that temperate crops, especially cereals, could be grown 200 km further south and 200 m higher for each 1°C increase in temperature. However, the potential range for these crops could contract in the south if winter chilling requirements are not met.

Sources: Salinger et al., 1990; Sirotenko et al., l991; CCIRG, 1991; Singh & Stewart, 1991; Downing, 1992; Menzhulin 1992; Pimentel et al., 1992; Rosenzweig et al., 1992; Sirotenko & Abashina, 1994; CCIRG, 1996.

Impacts of climate change on non-crop food production

Livestock production

In common with crop production, livestock production is sensitive to climate variables. Climate change could affect both livestock itself and dairy production. Quantitative estimates of impacts of future climate change on livestock are few, however, although the effects of weather and extreme events on animal health, growth and reproduction have been well-documented (Bianca, 1970; Rath et al., 1994). Heat stress, for instance, is known to have a variety of detrimental effects on livestock, with significant effects on milk production and reproduction in dairy cows (Johnston, 1958; Thatcher, 1974; Furquay, 1989). Additionally, young animals have been observed to be much less tolerant of temperature variation than adult animals (Bianca, 1976).

Thus in warm regions, higher temperatures would be likely to result in a decline in dairy production, reduced animal weight gain and reproduction, and lower feed-conversion efficiency (Hahn, Klinedinst & Wilhite, 1990; Baker et al., 1993; Klinedinst et al., 1993; Rath et al., 1994). More mixed impacts are predicted for cooler regions. If the length and intensity of cold periods in temperate areas are reduced by warming, feed requirements may be reduced, survival of young animals enhanced and energy costs for heating of animal quarters reduced. But intensive farming operations involving frequent cropping, mechanization and application of chemicals, could be subject to negative impacts arising from erosion and groundwater pollution as a result of increased precipitation (Parry et al., 1988; Baker et al., 1993; Klinedinst et al., 1993).

Climate change would also affect livestock through its impacts on disease. Incidence of protozoan diseases of livestock and other animals for instance, such as trypanosomiasis, theileriosis and babesiosis, are likely to be affected by climate change, since most of them are transmitted by vectors such as ticks and flies, the development stages of which are often heavily dependent on temperature. Thus in the early 1990s, for instance, a series of unusually warm winters enabled the *Culicoides* midge, which carries African horse sickness to establish itself in Spain. A second example refers to East Coast Fever, a major cattle disease in Africa. A quantitative model simulation of the disease vector — the *Rhipicephalus appendiculatus* tick — identified a three-fold variation in the duration of the tick's life cycle (i.e. from egg to adult) when average temperature was "set" ± 5°C higher or lower than that which would normally be experienced in the tick's geographical range (Byrom & Gettinby, 1992). Similarly, the US Environmental Protection Agency has identified several infectious diseases — such as the horn fly in beef and dairy cattle, and insect-borne anaplasmosis infection in sheep and cattle — which could increase in incidence following climate change (Rosenzweig & Daniel, 1989). Sheep, cattle, goats and horses are also vulnerable to an extensive range of nematode worm infections, most of which have development stages influenced by climatic conditions.

Measures to counteract the impacts of climate change upon livestock could include:

- closer management (particularly in warmer areas);
- adoption of new breeds in areas of moderate climate change;
- introduction of different species in areas of extreme climate change.

Abel and Levin (1981) conclude that, for developing countries, livestock are better able to survive severe weather events such as drought than are crops, and therefore a better option in terms of income protection and food security, albeit often not affordable.

Fisheries

On average, humans derive around one-fifth of their animal protein intake from fish (Weber, 1994a). Among some of the world's poorer traditional coastal communities, this proportion is considerably higher. Fish products are also used, increasingly, as fertilizer, medicine and livestock-feed supplement.

Almost half the world's commercial fish catch comes from coastal upwelling ecosystems, which represent just one-thousandth of total ocean area. Much of this catch consists of pelagic fish. The three major types of biological process that are crucial to the maintenance of the breeding areas or "fish nurseries" of coastal pelagic fish and many other types of fish are: *enrichment* via the upwelling of cold nutrient-rich waters; *concentration* of nutrients due to convergence, frontal formation and water column stability, and *retention* or dispersal of plankton (Bakun, 1994).

Wind intensity also plays a crucial role in maintenance of this type of coastal ecosystem. For instance, the success of fish reproduction is generally highest at intermediate wind intensity. Conversely, low winds result in a lack of nutrient enrichment, while high winds, due to increased turbulence, lead to excessive offshore transport of larvae and fish, dispersion of small food particles, displacement of algae to lower levels too deep for photosynthetic activity, and reduced larval grazing on plankton.

As Earth revolves in an easterly direction, coastal upwelling is particularly intense on the eastern boundaries of oceans. If the contrast in temperature between coastal land and ocean becomes greater following climate change, due to comparatively quicker terrestrial warming, winds caused by advection that increase coastal upwelling can be anticipated. This would result in a larger food supply for fish populations since more nutrients would be brought to the ocean surface.

As for ocean warming, although this will occur more slowly than warming on land, it could nevertheless lead to significant changes in ocean currents and nutrient upwelling. Phytoplankton production which forms the base of the aquatic food-web could be affected particularly adversely, leading to shifts in the distribution, migration and productivity of many fish species (Bakun, 1990; Glantz, 1992). Additionally, the sensitivity of zooplankton to UVR could mean that stratospheric ozone depletion contributes to further weakening of the aquatic food-web. (Unlike the phytoplankton upon which they feed, zooplankton are not protected from UVR by chlorophyll.) If fish stocks decline as a result of these changes, seabird and sea mammal populations will decline too (Roemmich & McGowan, 1995).

Increased climate variability and more frequent ENSO events may perturb ocean circulation yet further, with consequent shifts in fish communities. ENSO events have been associated with major collapses and shifts in communities of small pelagic fish. The collapse of the Peruvian anchovy fishery, the world's largest known fishery, for instance, coincided with the 1972 El Niño (UNEP, 1994b). Sardine populations off Peru and Chile subsequently became increasingly dominant during the 1970s and 1980s, while in the Benguela current off South Africa, the reverse occurred (Lluch-Belda et al., 1992). Other biomass "flips" took place during this period, some associated with overfishing, others apparently due to climatic changes (see also Chapter 6).

As well as geographic range, the timing of reproduction and body growth of cold-blooded animals such as fish are obviously highly sensitive to temperature (Kawasaki, 1991). Ocean warming may therefore extend the growing season for some fish species. In lakes and reservoirs, particularly at high latitudes, fish production could also increase, provided autumn and spring inversions are not affected by higher average temperatures (Schlesinger & McCombie, 1983). Meisner et al. (1987) forecast that the commercial production of major fish species in large lakes would increase by 20% in response to a 2°C rise in water temperature. In the short term, the productivity of all fisheries dependent on natural waters could rise if nutrients leached from soil are washed into water resources following increased or more intense precipitation. In coastal areas, such an effect would be amplified by the combined effects of sea-level rise and increased tidal range. Increased productivity of this kind appears to have occurred recently in southern USA, where sea-level rise is being exacerbated by land subsidence (Zimmerman et al., 1991).

To be fully understood, however, the potential impacts of climate change upon fisheries must be examined within the framework of ecosystem dynamics. An example concerning salmon illustrates this well. Along the north-west US Coast, salmon populations move north into Alaskan waters when temperatures increase. But this exposes them to mackerel predation, with the result that mature salmon stocks show a decline two years later. (The life cycle of salmon is four years.) In short, the biological impact of a warming period on salmon stocks can be appreciated only by understanding shifts in associated predator–prey relationships.

Human activities evidently impinge considerably upon ecosystem dynamics. Between 1950 and 1989, the world fish catch expanded from 22 million to 100 mmt (Weber, 1994b). Far outstripping the growth rate of the human population, this more than doubled seafood availability per person, from 9 to 19 kg. But overfishing is causing fish catches to decline; between 1990 and 1993, the total fish catch fell by slightly more than 7% (Brown, 1994). In fact, the catch extracted from most ocean fisheries is non-sustainable, that is, it exceeds the maximum yield that can be extracted without risk of diminishing future yields (Kane, 1993). Fourteen of seventeen major marine fisheries are already either fully or over-exploited (FAO, 1994). For example, cod populations in Atlantic waters off the north-east USA and Canada have declined through overfishing, as have Pacific salmon populations and fish populations of the Caribbean coral reef systems. Likewise, changes in the demersal fish community of the Newfoundland continental shelf, as a result of human exploitation, have reduced the biomass and numbers and size of many species (Haedrich, Hutchings & Horne, 1994). Fisheries that have already been weakened would be highly vulnerable to any future stresses that could arise due to global change.

Habitat destruction is also taking its toll on fish populations. Some 70% by mass of marine animals rely on coastal areas such as wetlands, mangrove swamps or rivers for spawning grounds (Everett et al., 1996). But in temperate countries wetland loss continues apace, while in tropical countries, more than 50% of mangroves have been destroyed. Sea level rise could result in further wetland and mangrove loss through inundation and salinization.

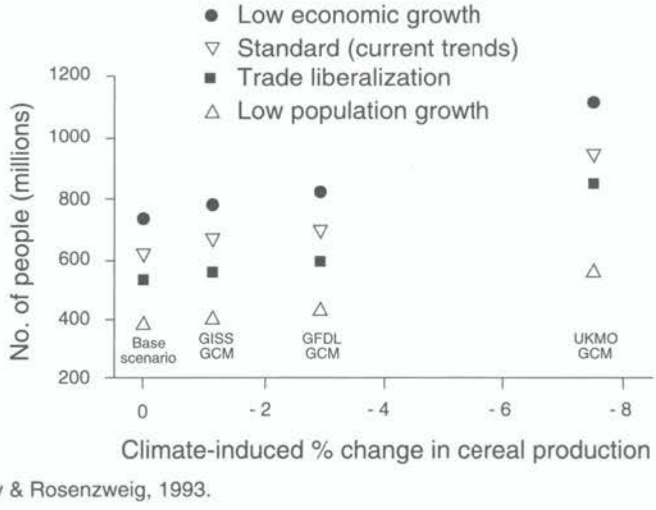
Fisheries are also suffering the adverse impacts of pollution. About one-third of the world's urban population lives within 6 km of coastline and contributes considerably to the pollution that reaches the seas. Heavy metals and various often chlorinated organic chemicals — which can bioaccumulate — contaminate fish, posing a risk to the health of people who consume them. In particular, tens of millions of tons of nitrogen and several million tons of phosphorus are added to the seas through mismanagement of sewage, and as a result of run-off following large-scale agricultural application of fertilizers. These "nutrient" chemicals cause eutrophication which contributes to the growth of algal "blooms". These can harm fish directly by damaging and clogging gills, and indirectly by lowering dissolved oxygen levels. Farmed fish are especially vulnerable since they cannot escape from such blooms. Eutrophication also stimulates proliferation of phytoplankton, some of which can cause serious illness and death in humans. These phytoplankton can enter the food chain if shellfish species have consumed large quantities of algae. The number of people affected annually in this way is small, but the resultant publicity can lead to serious economic loss since contaminated food supplies, or food supplies that are suspected of being contaminated, are kept out of the marketplace (Everett et al., 1996) (see also Chapter 4). The greater the importance of fisheries to a local economy, the more serious the economic loss.

Climate change may thus exacerbate in a number of ways the production losses that are already being incurred by fisheries. Traditional fishing communities and some developing countries with economies that are less diversified will be affected most. However, the impacts of climate change need not be negative everywhere, and adaptive measures (such as enforcement of fish quotas, intensification of fish farming) could do much to compensate for any losses. Adaptive measures will depend largely on the economic and social organization of the society in question.

Cereal grain supplies, food costs and the risk of hunger

Studies have suggested consistently that climate change could threaten food security in the poorer countries of the semi-arid and arid regions (Rosenzweig et al., 1993; Reilly et al., 1996). Countries already struggling with large and growing populations and marginal climatic conditions, and with minimal capacity for adaptive change, would be the most vulnerable to food shortages and malnutrition (Leemans, 1992). Indeed, in Africa, over 100 million people are already "food insecure" — that is, at risk of serious food shortages and starvation — many of them in the arid Sahel region and in circumstances where their population exceeds or is projected to exceed their country's "carrying capacity" (King et al., 1995).

Fig. 5.2. Projected number of people at risk from hunger in the year 2060: base scenario (no climate change) vs. three GCM-based climate change scenarios (CO_2-doubling, with CO_2 fertilization) for four sets of background trends. For each model global cereal yield declines, particularly in developing countries.



Based on: Parry & Rosenzweig, 1993.

Box 5.2. Predicting crop yields and prevalence of hunger

The potential effects of climate change on food production and the number of people at risk of hunger have been estimated with an integrated mathematical model by Parry and Rosenzweig (1993) (see also Fig. 5.2). Three different GCM-based equilibrium climate change experiments were used (GFDL = atmospheric carbon dioxide (CO_2) level increased to 600 ppmv, 4°C temperature rise, 8% increase in precipitation; GISS = atmospheric CO_2 level increased to 630 ppmv, 4.2°C temperature rise, 11% increase in precipitation, and UKMO = atmospheric CO_2 level increased to 640 ppmv, 5.2°C temperature rise, 5% increase in precipitation).

If CO_2 fertilization is not taken into account, total crop yield would be affected negatively under each of the climate change scenarios. For the less severe scenarios — i.e. GFDL and GISS — major adaptation through planting of different species or varieties could compensate almost completely for the negative impacts of climate change on yields. But under the UKMO scenario, it appears that, even if CO_2 fertilization is taken into account, adaptation would not be sufficient in most countries. Estimates of subcontinental yield differences, especially for lower latitudes, are less reliable owing to regional variations in precipitation.

Assuming that population and economies will continue to grow to the year 2060, that technological development will continue, and that trade liberalization will increase gradually until the year 2020, it is estimated that world cereal production will grow from the 1795 mmt of 1990 to 3286 mmt by 2060, that cereal production in developing countries will surpass that of developed countries by 2025, and that food production, measured as net calories produced, will rise faster than demand.

The number of people at risk of hunger in developing countries was estimated to be 530 million in 1990 (or 10% of world population). If the above trends are applied, but climate change is not taken into account, this figure rises to 640 million by 2060. The forecasts evidently change when climate change is integrated with the crop yield model. Global cereal production — taking minor adaptations of current agricultural practices into account — then drops by up to 160 mmt (-5%) from the 2060 projection of 3286 mmt. Extensive adaptation, however, could virtually eliminate the negative impact of climate change on cereal yield, especially under the less severe climate change scenarios (GFDL and GISS).

In developed countries, minor adaptations to current agricultural practice could largely offset the negative effects of climate change, thus improving these countries' relative advantage on the world markets. While the number of people at risk of hunger in developing countries would be 640 million in 2060 when climate change is not taken into account, under the GISS scenario this figure drops by 12 million. But it rises by 120 million under the UKMO scenario, even when major adaptation is allowed for.

Source: Parry & Rosenzweig, 1993.

The cost of food on world markets would presumably increase if crop production declined in the world's mid-latitude mid-continental "bread-basket" regions: the US Great Plains, Ukraine, the Mediterranean and north European lowlands, the Australian wheat belt and Argentinian pampas. The economies of many countries could be affected negatively as a result. Populations already suffering from malnutrition might then face an increased threat to health and survival since countries that currently provide them with food aid might find themselves with less resources than formerly, and therefore less able to maintain aid levels.

Translating predictions of changes in world food-crop production into predictions of levels of human malnutrition and hunger is difficult, however. The models used must incorporate information on or predictions pertaining to world food trade, market prices, population growth, and economic disparities between countries (summarized in Box 5.2 and Fig. 5.2). A recent study estimated that the number of extra people who would be at risk of hunger in the year 2060 due to climate change would be in the range of 40–300 million; the width of this range reflects several different plausible trends in demographic, economic and world trade factors. The number of people who would be at risk of hunger in 2060 in the absence of climate change is estimated at 640 million (Rosenzweig et al., 1993).

The wider context

Food production, on land and at sea, is much influenced by environmental factors, many of which are aspects of or influenced by climate. But the various global climate change scenarios, and associated predictions of regional climate change, are subject to much uncertainty. So we do not know for sure how climate change will affect global food productivity. An added complication is that food productivity, availability and consumption are also linked to social, political, economic and technical factors. But such factors are not easy to foretell and, furthermore, not readily incorporated into quantitative estimates.

Biological resilience and technical adaptations may buffer some of the impacts of climate change upon crop productivity. However, it is generally considered that sustained, increasing climate change would eventually cause a downturn in world crop production. This is because agro-ecosystems entail complex, dynamic and interactive processes, and climate change could cause critical thresholds to be passed.

Such largely unpredictable phenomena could lead to severe disruption of livelihood among rural populations too poor to benefit from novel technologies or unable to risk the failure associated with alternative crops or new crop strains developed to resist the impacts of climate change. Human health may be affected in many ways. The diseases resulting from poverty and malnutrition may pose a specific challenge to the world community and efforts should be undertaken at an early stage to assist populations already under severe threat of starvation with developing non-agricultural sources of income, so that national food security can be increased through importation of food supplies.

Chapter 6

Extreme weather events

Modelling extreme weather events

Climate change is anticipated to manifest itself partly as change in weather variability (see Chapter 2). Relatively small changes in climate variability or mean climate could produce relatively large changes in the frequency of "extreme" weather events. Extreme weather events can be defined as infrequent meteorological events that have a significant impact upon the society or ecosystem at a particular location (see also Chapter 2). Although still subject to speculation, climate change could also affect the frequency of the El Niño/Southern Oscillation (ENSO) which amplifies climate variability around much of the world (see Chapter 2).

But predicting the effects of climate change on the frequency, timing and duration of extreme weather events is very difficult. This is partly because most GCM-based climate change experiments focus on potential changes in *mean* climate conditions (Katz & Brown, 1992). Furthermore, climate models are unable to describe extreme weather events adequately because they lack spatial and temporal resolution. (Extreme weather events are limited in time and space.) Thus climate change models indicate major regional differences in changes in future precipitation patterns, but are not yet sophisticated enough to predict with certainty the impact of climate change on, for example, local precipitation patterns or the frequency of tropical cyclones.

If the frequency of extreme weather events increases, the deaths, injuries, stress-related disorders and the many adverse health effects associated with the social disruption, enforced migration and settlement that these events entail, would also increase. The impacts of extreme weather events would be greatest on communities with the fewest technical and social resources. However, since each extreme weather event is unique in scale, timing, location and human societal context, this chapter describes the range of possible events and impacts, but does not attempt to quantify them.

Defining disasters

Disasters can be classified in a number of ways. A recent meeting of international organizations suggested the following grouping (IFRC, 1993):

- sudden natural, e.g. avalanches, floods, cyclones;
- long-term natural, e.g. droughts, desertification, epidemics, famine;
- sudden human-made, e.g. structural collapse of buildings.

However, more recently, WHO/IFRC/UNHCR (in press) recognized a fourth category:

- long-term human-made, e.g. climate change, caused by human activities.

Extreme weather events fall mostly into the first category, although it should be borne in mind that not all extreme weather events lead to a disaster. Examples include floods, wind storms landslides and forest fires. Some, however, such as drought, fall into the second category. It should be noted, though, that human activities may contribute to extreme weather events. In other words, the causes of a long-term natural disaster may lie in natural processes *and* human activities. Drought and desertification, for instance, may be the result of long periods of unusually dry weather conditions, combined with non-sustainable land-use practices, including forest clearance for crop production, and overgrazing by livestock. Indeed, the distinction between long-term natural and long-term human-made disasters is obscured by the severe impacts that human activities may have on natural processes. Long-term global environmental change has both natural and human-made components.

WHO/IFRC/UNHCR (in press) also take care to distinguish between emergencies and disasters. Thus an *emergency* represents a violent disruption of life in a community, and requires that the community affected take special measures to reduce loss of life, adverse impacts on human health, and damage to material goods, homes and infrastructure, and to return living conditions to normal. But a *disaster* occurs if the measures taken by the community fail to reduce losses and to return life to normal without substantial external assistance. In this chapter, however, "disasters" are more commonly referred to than "emergencies and disasters", since the sources from which information has been gathered tend to refer only to disasters. Nevertheless, use of the combined term "emergencies and disasters" is ultimately to be preferred, since it incorporates the idea that a disaster evolves from an emergency, and therefore may be preventable.

Current trends in extreme weather events and disasters

Some studies have observed an increase in the frequency of extreme weather events in recent decades, and in the number of people affected (see for example, Glickman, Golding & Silverman, 1992; IFRC, 1994; Noin, 1994). But data on the impacts of extreme weather events are often approximate or simply underestimates. Moreover, measuring such impacts is difficult because of problems relating to definition and accuracy (Noin, 1994). A recent calculation of the number of extreme weather events — including prolonged summer drought, winter floods and sudden downpours — that have occurred in the USA, found that the frequency of these events increased in the 1980s and has continued to increase during the 1990s (Karl et al., 1995). However, the Intergovernmental Panel on Climate Change (IPCC) has concluded that there is no clear evidence that sustained or worldwide changes in the frequency or intensity of such events have taken place in recent decades (see Chapter 2).

International reinsurance data show an upward trend in the national economic losses due to all kinds of disaster, albeit with considerable interannual differences in the frequency of these events. For example, for countries where the insured sums were known, natural disasters, including non-climate related events such as earthquakes and volcanic eruptions, resulted in losses of US$ 3 billion in 1960 and US$ 38 billion in 1992 (Berz, 1994). Table 6.1 shows the losses incurred during the ten most expensive climate-related disasters, principally hurricanes and floods, that occurred between 1986 and 1993. The losses suffered by the economies of industrialized countries were high largely because the value of the infrastructure that was destroyed or damaged was high.

However, it is clear that populations in developing countries are affected more by such events than are populations in developed countries. For example, the five tropical cyclones with the

Table 6.1. The ten most expensive climate-related disasters worldwide between 1960 and 1993

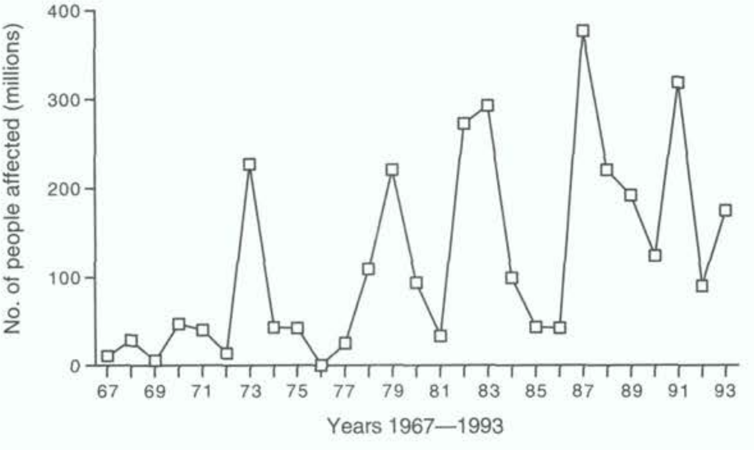
Year	Event(s)	Region	No. of deaths	National economic damage US$ million	Rank	Insured damages US$ million	Rank
1992	Hurricane: Andrew	USA	74	30 000	1	16 500	1
1990	Winter storms	Europe	230	15 000	2	10 000	2
1991	Floods	China	3074	15 000	3	410	9
1993	Floods	USA	41	12 000	4	1000	8
1989	Hurricane: Hugo	Caribbean, USA	61	9000	5	4500	4
1991	Typhoon: Mireille	Japan	62	6000	6	5200	3
1993	Winter storms	USA	246	5000	7	1750	6
1987	Winter storms	France, UK	17	3700	8	3100	5
1992	Hurricane: Iniki	Hawaii	4	3000	9	1600	7
1991	Cyclone, floods	Bangladesh	140 000	3000	10	100	10

Source: Berz, 1994.

highest recorded mortality occurred in Bangladesh (1970: 300 000 deaths; 1991: 140 000 deaths; 1985: 11 000 deaths), India (1977: 20 000 deaths), and Honduras (1974: 8000 deaths).Around 95% of the 250 000 deaths that occur worldwide every year as a result of natural disasters occur in poor countries. Moreover, although the economic losses of disasters are heaviest in rich countries (see Table 6.1), the socioeconomic impact of a disaster may be far greater in developing countries, if loss is considered as a proportion of GNP. Thus the impact of weather-related disasters in poor countries may be 20–30 times larger relative to GNP than in their wealthier counterparts (Mitchell & Ericksen, 1992). During 1989 the USA incurred losses amounting to at least 0.15% of its GNP as a result of natural disasters. Losses may have been even higher — ranging from 1 to 4% of US GNP — between the mid-1970s and 1988, when major droughts occurred (National Research Council, 1991). In Latin America, however, the general economic losses due to natural disasters may have amounted to between 2 and 3% of GNP over long periods. In specific years, much greater losses have been incurred (Jovel, 1989). For instance, floods and drought associated with the El Niño of 1982–83 led to losses of about 10% of GNP in countries such as Bolivia, Chile, Ecuador and Peru. This amounted to around 50% of their annual public revenue and put severe strain on already fragile infrastructures.

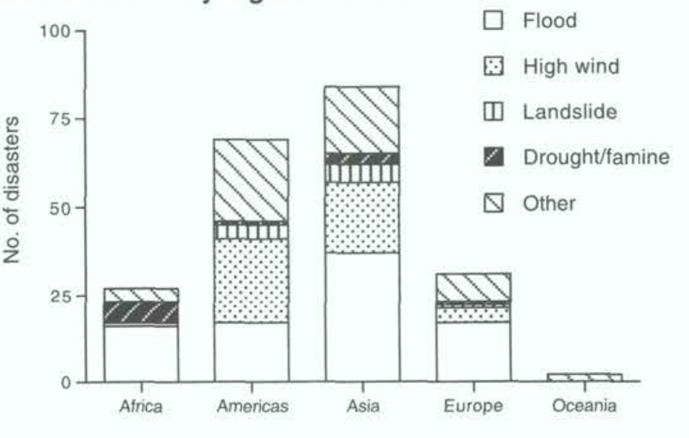
Although there are pronounced year-to-year fluctuations in the numbers of deaths due to disasters, a trend towards increased numbers of deaths and numbers of people affected did appear to develop between 1968 and 1991 (Fig. 6.1). The increase may be attributable to improved reporting or, in some cases, to the desire of governments to attract foreign aid. But the rise is too great to be accounted for solely by these explanations and may in fact also be due to the increasing vulnerability of populations. High rates of population growth, which in some areas has led to the concentration of populations in disaster risk zones, is a major contributory factor to this vulnerability. Thus in large shanty towns, structures tend to be extremely flimsy and located on marginal land, such as steep slopes, or on land subject to frequent flooding. Similarly, in those rural areas where agricultural productivity is low and land ownership and/or distribution unequal, the only land available to impoverished communities may be marginal land that has few natural defences against weather extremes.

Fig. 6.1. Number of people affected by natural disasters worldwide between 1967 and 1993. The number of people affected is defined as those requiring immediate assistance during an emergency situation, for example, for food, water or medical treatment



Source: IFRC, 1994.

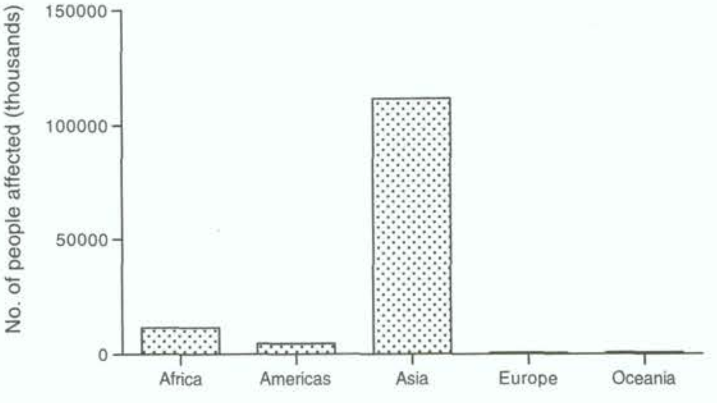
Fig. 6.2. Number of natural disasters by region in 1994



Source: IFRC, 1996.

Other includes: earthquake, volcanic eruption, avalanche, cold spell, heat wave, etc.

Fig. 6.3. Annual average human impact of natural disasters, averaged over 25 years (1970–1994) by global region



Source: IFRC, 1996.

Table 6.2. Number of natural disasters[a] over 25 years (1971–1994) by global region and type. High winds (including cyclones, hurricanes and typhoons) and floods account for the largest number of disasters, with the largest proportion of events occurring in Asia

	Africa	America	Asia	Europe	Oceania	Total
Drought and famine	272	51	88	15	15	441
Flood	168	373	628	138	139	1466
High wind	84	428	683	214	200	1609
Landslide	12	87	96	21	10	226
Earthquake	40	129	234	163	85	651
Volcanic eruption	8	31	45	16	5	105
Other[b]	218	90	190	95	7	600

[a] The criteria for a "natural disaster" are 10 deaths, and/or 100 people affected, and/or an appeal for assistance.

[b] Other includes: avalanche, cold spell, heat wave, insect infestation, tsunami.

Source: IFRC, 1996.

During the past two decades the human impacts of climate-related disasters have been considerable. Droughts, famines and floods accounted for more than half of all the people affected, although floods and storms with high winds destroyed the largest proportion of homes (IFRC, 1995). Very large numbers of people have been killed or affected by famines associated with drought, such as the Sahelian famines in Africa of the early 1970s and mid-1980s. The total ratio of persons affected to persons killed for all types of natural disaster is estimated to be around 800:1 (i.e. one out of 800 people affected by disaster will die) (IFRC, 1994).

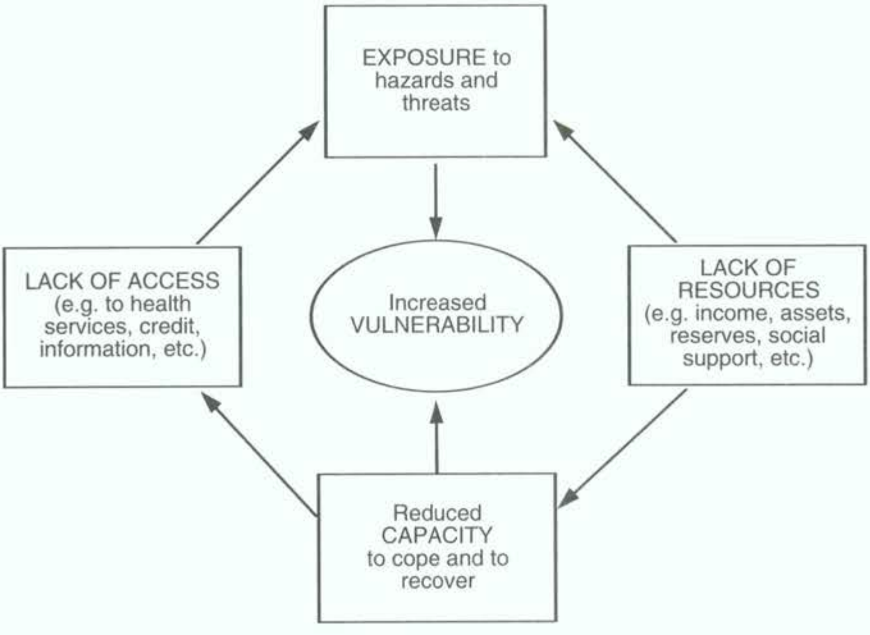
Some parts of the world are especially vulnerable to natural disasters. For extreme weather events the principle risks zones are tropical Asia and tropical America (Fig. 6.2; Table 6.2) (Noin, 1994). The greatest numbers of deaths are due to famine triggered by drought and storms with high winds (IFRC, 1995). Africa is the continent most affected by famine. However, to date, the greatest number of people affected by natural disasters has been in Asia, principally on account of its higher population density and larger population (Fig. 6.3).

Societal impacts of extreme weather events

Assessment of the human impacts of extreme weather events should focus on the vulnerability of populations and how this is affected by social, economic and political factors (see Fig. 6.4). Many of the populations affected most adversely by these events live in highly impoverished circumstances. Impacts on these populations are usually attributable to a complex mix of natural hazards and human action. For example, drought can exacerbate tensions over limited resources and lead to conflict (Blaikie et al., 1994). The precise nature and extent of impacts also depends upon the anticipation of risk and the assumptions made about the level of protection that is needed. However, these assumptions in turn depend on knowledge concerning the frequency and intensity of extreme weather events. With global climate change, this frequency and intensity are likely to change, but not in any predictable manner (Swiss Re, 1994).

An extreme weather event which appears to trigger a disaster does so against a social background. Evidently, though, the relative contribution of the geophysical and biological processes on the

Fig. 6.4. Diagrammatic illustration of vulnerability to disasters



Source: WHO/IFRC/UNHCR, in press.

one hand, and societal circumstance and processes on the other, varies from case to case. The "pressure and release" model is a relatively simple tool demonstrating how a disaster can occur when a natural hazard affects a vulnerable population (Blaikie et al., 1994). The model has three linked components: root causes, dynamic pressures and unsafe conditions. Root causes include the limited access of populations to power and resources, and the ideological and political systems that determine access to resources. Dynamic pressures include factors such as rapid population growth, urbanization, arms expenditure, debt repayment and deforestation. Unsafe conditions might include a fragile physical environment (for example, an unstable natural environment or a poorly-designed building), an unstable local economy, lack of disaster preparedness, and current high prevalence of disease, which would slow population recovery following a disaster, or lead to rapid spread of disease in its aftermath. Overall risk can thus be conceived as the joint product of the actual event and the vulnerability of the population. Other factors, such as lack of appropriate skills, and lack of training and local institutions, are also relevant since they impede development of the mechanisms necessary for coping with climatic hazards.

The speed of environmental, social or economic change may also partly determine the vulnerability of a specific population. A population experiencing rapid population growth, rapid deforestation or sudden population displacement, for instance, would be far less able to cope with the impacts of an extreme weather event than a population for whom environmental and social conditions are stable. The particular age structure of a population can also enhance vulnerability. In many developing countries as much as 50% of the total population is under 15 years of age; large groups of children who are without shelter or familial protection are becoming "street children". Growth in the size of the elderly population is also marked in many countries; over a 10-year period the world's elderly population will have increased by 43%, with nearly three-quarters of this increase occurring in developing countries (Blaikie et al., 1994). The young and old are most at risk in disaster situations because they are less mobile, have less resistance to disease and possess fewer resources.

The "access" model is another model that has been developed to increase understanding of the impact of disasters. It focuses on integrating natural forces with social frameworks, and demonstrates how individuals' access to the resources necessary for recovering from the impacts of a disaster is tied to their social and economic circumstances. Using the access model, Winchester (1992) examined the impacts of tropical cyclones in coastal Andhra Pradesh in south-east India, and observed that these may differ dramatically between a poor household and a wealthy household. Wealthy farmers may receive advance warning of the cyclone by radio which allows time for evacuation. Moreover, their homes are generally better constructed than those of poor householders, and if rebuilding is necessary in the wake of a disaster, they often have the requisite means. They may also have savings with which to purchase replacement livestock and agricultural equipment. A poor family, as well as being at greater risk of harm, may have few or no resources for re-establishing itself. Degree of vulnerability to disaster also differs according to the type of natural hazard. For instance, in the case of drought or famine, vulnerability is reduced if the individual or family is able to earn enough money to buy food and/or is entitled to food rations provided by governmental or nongovernmental relief organizations.

These approaches to analysing the impacts of disaster indicate that the impacts of an increased number of extreme weather events following climate change will depend not only on their frequency and severity, but also on a range of social factors which determine population vulnerability. This increases the difficulty of predicting the impacts of future disasters and has important implications for prevention and mitigation (see Chapter 10).

Floods

River flooding is caused mainly by sudden increases in precipitation or soil saturation following precipitation of several weeks duration. Climate change is expected to cause changes in the timing, regional patterns and intensity of precipitation events, and, in particular, in the number of days when heavy precipitation occurs (see Chapter 2) (Arnell et al., 1996).

Recent floods in north-west Europe (1993, 1995) and the USA (1993) were caused primarily by unusually high precipitation combined with saturation of soil due to earlier precipitation. They are an example of what might be expected as a result of global climate change, although they cannot be taken as proof that it is already taking place. Nevertheless, increases in riverflow and rainfall have been observed in northern Europe and the USA that are consistent with climate change projections (Weijers & Vellinga, 1995). Using a GCM-climate change scenario, hydrological modelling indicates that all major rivers at high latitudes will show increases in run-off. Some broad regional assessments have also been made of the likelihood of increased river flooding due to projected changes in precipitation (Arnell et al., 1996). Increased coastal flooding can also be anticipated if sea level rises due to climate change, irrespective of any fluctuation in the frequency and severity of extreme weather events such as storms and very high precipitation (see Chapter 7).

Table 6.3. Life-threatening characteristics of floods

- Absence of warning of a flood: either "official" warning or warning derived from environmental cues e.g. heavy rain.
- High floodwater velocities: likely in hilly or mountainous areas or where streams disgorge onto plains from upland areas; in river valleys with steep gradients; in areas behind flood embankments or natural barriers which may be breached or overtopped, or below dams which may burst.
- Rapid speed of flood onset: likely in areas where streams are "flashy" i.e. rise and fall rapidly; these are usually urban areas or arid rural areas where soil surface becomes compacted and hard; or in areas where high flood water velocities may be expected.
- Deep floodwater (where floodwater exceeds one metre in depth): occurs in or close to river channels; in depressions which may not be easy to identify by eye; behind overtopped flood embankments and in basements of buildings.
- Long-duration floods: likely where land is flat, flooding is extensive, river gradients are very low, channels are obstructed, and floodwater becomes trapped behind natural or artificial barriers.
- Flood has more than one peak: not untypical in complex river systems where tributaries contribute to river flows, or where flooding is tidal.
- Debris load of floodwater: usually greatest in high-velocity floods; floodwater may contain trees, building debris, etc., which may either provide floating refuge or endanger life.
- Characteristics of accompanying weather: especially windy, unusually cold or hot weather.

Floods may display combinations of these characteristics

Source: Parker & Thompson, 1991.

In tropical areas, heavy rainfall also occurs during storms in the wet season and can result in flooding. But even some semi-arid and arid zones are vulnerable to sudden, unexpected flash floods. The potential for increased flooding following climate change would be exacerbated by erosion associated with deforestation and overgrazing, both of which are now widespread in many developing countries. Such environmental degradation also increases run-off and the severity of flooding, and contributes to landslides. Other factors which increase the potential danger of floods are listed in Table 6.3.

Flooding can cause many deaths and injuries. In the USA, for instance, flash floods are the leading cause of weather-related mortality (French & Holt, 1989). The public health impact of floods also includes damage to or destruction of homes and displacement of their occupants. Although much of the literature focuses on catastrophic floods, it is likely that more frequent but less severe flooding also has significant impacts on health.

Most of the deaths and injuries caused by a major natural disaster of sudden impact such as a flood or storm, occur within a few hours of the event starting. Therefore, the main cause of death during floods is drowning (see Box 6.1). The small fraction that occurs later includes deaths resulting from initial injuries, and deaths due to outbreaks of disease following a breakdown in sanitation services, or shifts in disease vector populations. The ratio of deaths to injuries during floods has been estimated at around 1:6 (PAHO, 1981).

Following a flood, sanitation problems due to disruption of water or sewage systems and prevention of solid-waste collection and disposal, often contribute to increased infectious disease incidence.

Box 6.1. Death by drowning

The Hwang He (Yellow) River in China is probably the most flood-prone river in the world. Flooding of this river in 1887 — the most lethal flood in recorded history — caused the deaths of an estimated 900 000 people and rendered another 2 million homeless. In northern China in 1969, around half a million people, and a further several hundred thousand in Shandong Province, north-east China, may have perished in floods. Europe has also experienced major loss of life due to flooding. In 1953, 1795 people died in the Netherlands after several dikes were breached. In 1963 in northern Italy, a large landslide collapsed into a hydroelectric reservoir after heavy rains, causing more than 100 million tonnes of water to breach a dam, destroying the town of Longorone and several hamlets, and killing around 2000 people.

Sources: French & Holt, 1989.

This is particularly so if, temporarily at least, living conditions become crowded and maintenance of personal hygiene difficult (see page 96). An analysis of the causes of illness and death in the population displaced by catastrophic floods in Bangladesh in 1988, found that diarrhoea was the most common illness, followed by respiratory infection. The most common cause of death for all age-groups, except those over 45, was watery diarrhoea (Siddique et al., 1991). Increases in diarrhoea (and malaria incidence) were also observed following floods in Khartoum, Sudan, in 1988.

Decreases in the nutritional status of children also commonly occur after floods. This was the case following the aforementioned floods in Khartoum. Likewise in rural Bangladesh, the proportion of severely malnourished children increased after monsoon flooding (Woodruff et al., 1990; Choudhury & Bhuiya, 1993). However, since data on baseline morbidity for the period preceding a flood are often not available, careful comparisons of the effect of flooding on levels of disease and nutrition is difficult.

Flooding may also result in the release of dangerous chemicals from storage sites and waste disposal sites into floodwaters, and the widespread destruction of food supplies (Alexander, 1993). In 1976, large amounts of pesticides were swept away by floodwater following the collapse of a dam in Idaho, USA. Although 60% of the pesticide containers were later recovered, high levels of polychlorinated biphenyls and DDT (dichlorodiphenyltrichloroethane), that exceeded US Food and Drug Administration tolerance levels, were found in fish (Perry, 1979).

Any increase in heavy precipitation and consequently in run-off from agricultural lands, would also be likely to increase contamination of water with chemicals such as pesticides (Thurman et al., 1991; 1992). For example, flooding in the midwest USA in 1993 caused wide dispersal, including and beyond the Gulf of Mexico, of microorganisms and chemicals from agricultural lands and industrial sites. Human exposure to toxic agents such as these may then occur if water or animals that have become contaminated are consumed. Additionally, uptake of a pesticide such as aldrin may be enhanced in rice, plants and grains grown on flooded soils, leading to higher exposure levels among humans and animals. Chemicals may also persist for longer in flooded soils than in non-flooded soils (Singh et al., 1985).

Human disruption and stress have been perceived consistently as two of the most significant impacts of flooding (Green & Penning-Rowsell, 1986). The actual damage to an individual's dwelling and possessions are usually considered to be much less important. Stress appears to occur as a result of the discrepancy between the resources that the individual can mobilize and the challenge with which he or she is confronted (Lazarus, 1966). In the case of floods, the resources that can be mobilized may include household disposable income, level of savings and insurance, social competence, and health and social support systems.

However, research in this area is beset by methodological difficulties. For instance, distress and ill-health must be clearly defined and differentiated. Stress at the time of the flood can, if the event is of short duration, be distinguished from subsequent stress. However, a flood may not act as a single acute stressor. A period of disruption may follow the flood, and worry about flooding in the future may be long-term (Green et al., 1994). Insurance payments and other forms of financial aid may reduce the severity of long-term structural damage and loss, thereby alleviating disruption and stress. Additionally, rehabilitation of infrastructure and housing can help to minimize any damage due to subsequent floods and serve to reassure the population.

To date, studies of the social impacts of floods have been relatively limited. Much of the work has focused on flood victims in developed countries. Preliminary analysis of UK data, for instance, does not indicate that social support reduces "event stress" or "worry" significantly, although considerable importance appears to be attached to support received to re-establish households. In view of the potential increases in flooding that climate change might entail, more work should be carried out in this area, and in a variety of cultural settings.

Box 6.2. Climate change and famine

The Sahel region in sub-Saharan Africa, between the latitudes of 13°N and 17°N is particularly vulnerable to drought. Its annual mean temperature is 28–30°C and annual precipitation averages between 250 and 500 mm. Seasonal drought occurs from October to June during the normal dry season; contingent drought occurs if the normal rainy season is delayed. This was the case between 1969 and 1973, and subsequently in the mid-1980s. In 1973 around 100 000 people died as a result of drought in the Sahel; 25% of all cattle in the area died or were slaughtered. In the following year, drought rendered 200 000 people in Niger dependent upon food aid and a similar number refugees in Mali, while around 250 000 people were made destitute in Mauritania. Combined with overcultivation and overgrazing, drought leads to ever-increasing desertification, with long-term effects on the capacity of the land to support a local population. Since 1925 more than 650 000 km^2 of land on the southern edge of the Sahara have ceased to be productive. The impacts of climate change on periods of drought are likely to have major consequences for human health in the Sahel and other parts of the world threatened by desertification.

Source: Alexander, 1993.

Droughts

The health consequences of drought include diseases resulting from a breakdown in sanitation, particularly faecal–oral (i.e. primarily diarrhoeal) and water-washed diseases (such as scabies and conjunctivitis) (see Chapter 4). Other conditions such as trachoma are also associated with poor hygiene and similarly tend to increase if water resources become depleted. Drought can also lead to a deficiency in micronutrients owing to reduced consumption of fresh fruit and vegetables. For example, vitamin A deficiency frequently becomes more common in drought conditions, affecting susceptibility to infections of the respiratory and gastrointestinal tracts. In severe cases, vitamin A deficiency can lead to blindness due to xerophthalmia.

However, the health impacts of drought on populations occur primarily via drought's impacts on food production. In the most extreme case, famine, the number of deaths associated with insufficient food consumption increases substantially (see Box 6.2) (Toole & Foster, 1989). In early 1991, for instance, 4.3 million people were facing starvation in north-east Africa as a result of drought (Alexander, 1993). Famine often occurs when a pre-existing situation of malnutrition worsens. Frequently, several factors are involved, including inability of the population to produce food because of adverse climatic or other environmental conditions and/or absence of appropriate food aid. The latter may include a collapse in the marketing system due to political, environmental or economic crises. Additionally, these factors may have a cumulative or synergistic effect. For example, a breakdown in the reserve food supply system due to the sale of grain or livestock reserves might be exacerbated by conflict and breakdown in law and order.

The signs and symptoms of protein-energy malnutrition are well known and include weight loss, weakness, apathy, cachexia, reduced mobility, anorexia and ultimately death. Young children are particularly likely to experience these symptoms and marasmus is the commonest type of protein-energy malnutrition to which they are susceptible. Past examples include incidence of kwashiorkor in 1969 in Biafra, Nigeria, when children were given cassava which provided energy but virtually no protein (Mayer, 1969). More recently, prevalence rates of malnutrition as high as 70% were recorded in children in Ethiopian refugee camps in 1985. Also in 1985, in both Ethiopia and Sudan, children between the ages of one and four suffered the greatest excess mortality of any age group.

Many famine-related deaths are linked to infectious disease; reduced immunity due to starvation can play a significant role. Case-fatality rates of 50% for measles, for instance, were reported for children with kwashiorkor during the Nigerian civil war (Smith & Foster, 1970). Diarrhoeal diseases are also common during famine, especially in refugee camps, where water supplies are often unsafe.

Food toxicity is an additional problem in times of famine. People who are starving are sometimes tempted to eat unfamiliar foods without taking the necessary precautions. For example, during 1983–1984 in Mozambique, many deaths were ascribed to consumption of the toxic parts of cassava plants (Cliff et al., 1984).

Famines are usually of slow onset and early warning signals accordingly ample. Famine is therefore a largely preventable phenomenon. But in the event of famine, relief programmes should include nutritional and mortality surveillance, and community-based provision of adequate rations for families. In the early stages of a famine, specific health programmes have often focused on preventive action such as measles vaccination, control of diarrhoeal disease, and supplementary and therapeutic feeding. Rehabilitation of food production and distribution systems is also important, although supplying food stocks rapidly to large populations can be very difficult. For instance, a single four-wheel drive vehicle can only carry sufficient food for a daily ration for about 20 families (Knott, 1987). In several arid and semi-arid zones (such as the Sahel, see Box 6.2), strict land-use planning and anti-desertification measures will be essential if, in a warmer world, community dependence on food aid is to be minimized.

Forest and range fires

Climate change may increase the susceptibility of some forests and rangelands to fires. Evidently, these are more likely when temperatures are high and soil moisture content low. In particular, forest fires are triggered by drought, heat waves, low humidity and high winds, particularly in the wooded and warmer regions of Australia and the USA. The widespread "Ash Wednesday" bushfires in Australia in 1983 were due partly to the preceding drought (associated with the 1982–1983 El Niño) which had dried out vegetation and soil.

"Environmental fires" are divided into several categories. "Surface fires" affect ground-level vegetation only, and are fairly easy to control, although they may travel at high speed. "Crown fires" burn forests up to the crowns of trees and result in extremely high temperatures. "Dependent crown fires" occur when flames from surface fires ignite tree crowns. "Running crown fires" occur when winds are strong, vegetation extremely dry, and the crown fire travels ahead of surface fires causing new spot fires. Ground fires occur where there are large amounts of sub-surface organic materials, such as peat and humus. They tend to spread slowly but can destroy root systems. The spread of fires also obviously depends on wind speed and consistency.

In addition to the direct effects of fires on human health from burns and smoke inhalation, forest fires release large amounts of particulate matter into the atmosphere. Additionally, loss of vegetation on slopes may lead to soil erosion and increased risk of landslides. Such a process is often exacerbated when an urban population expands into surrounding hilly and wooded areas. Nevertheless, fires can have positive impacts on ecosystems; for instance following burning of grasslands, grasses may grow more vigorously for several years since the ash created by burning is a source of mineral nutrients, and the dark surface created by burning decreases the likelihood of ground frost (Alexander, 1993).

Wind storms

Wind storms are a major cause of climate-related deaths and injuries. (Box 6.3 defines the various categories of wind storm.) Their frequency and intensity could be increased in regions where climate change leads to more frequent atmospheric pressure shifts and greater pressure differentials.

Flooding is often associated with such storms. A hurricane may produce 200 billion tons of water a day, in addition to liberating a hundred billion kilowatts of heat from the condensation of moisture. Moreover, where it comes ashore, the associated storm surge may lead to severe coastal flooding; around 90% of hurricane fatalities are due to drowning following the storm surge.

Box 6.3. Wind storms

In this book, wind storms are categorized as follows:

- *Tropical cyclones* are defined as fierce tropical storms that originate in the zone found between 5°N and 20°S of the equator, with winds rotating inwards around an area of low pressure and wind speeds exceeding 118 km/h. These storms are large-scale meteorological phenomena: the entire spiral storm system may extend more than 1600 km across. Tropical cyclones begin in areas in which sea surface temperature exceeds 27°C, usually during summer and autumn, when seas are at their warmest and intense pressure gradients produced. The centre or "eye" of a cyclone consists of an area of very low pressure, around which strong winds of up to 320 km/h occur. This eye is calm and subject to light winds only. An extra-tropical cyclone is a cyclone that originated in the tropics but which has since moved into non-tropical areas. Most of the flooding associated with tropical cyclones is due not to heavy precipitation, but rather to what is known as the storm surge. Winds and low pressure around the eye may raise the sea surface by as much as 6 metres above normal local sea level; this body of water may travel for several kilometres inland. Serious coastal flooding can result, especially if the storm surge strikes at high tide.
- *Hurricanes* are tropical cyclones that occur in the Caribbean.
- *Typhoons* are tropical cyclones that occur in the Pacific.
- *Tropical storms* have wind speeds of 62 to 118 km/h, and are intermediate in space and time.
- *Tornadoes* are wind storms with a fiercely rotating column of air generated by severe imbalances between air temperature and pressure. They are short-lived phenomena, cover a much smaller area than tropical cyclones — often less than 500 m in diameter — and are poorly understood. Nevertheless, tornadoes can cause severe structural and other damage since their wind speeds may reach 500 km/hr. Most tornadoes occur in the USA.

Source: Lee, 1993.

Impoverished populations in low-lying areas would be particularly vulnerable to an increase in cyclonic activity. Some idea of potential impact can be gained from the impacts that recent cyclones have had on populations. One of the most serious cyclones this century occurred in 1970 in Bangladesh: mortality ranged from around 5% inland, to around 46% on the coast. The populations of some fishing villages were almost totally annihilated. The highest survival rate was among middle-aged men, while women, particularly those over 60, were more likely to be killed or seriously injured. Additionally, two-thirds of fishing activities along the coasts and plains in Bangladesh were destroyed, along with 125 000 livestock animals (Alexander, 1993). Human populations also commonly suffer crush injuries and major lacerations during such disasters. In the cyclone of 1970, in Andhra Pradesh, India, many of the victims died when wind and rain caused houses to collapse (Sommer & Mosley, 1972). Between 1900 and 1982, 31 hurricanes affected the USA, each causing 25 or more deaths. The largest death toll was as a consequence of a hurricane in Texas in 1900, which caused 6000 deaths.

Tornadoes affect much smaller land areas than do cyclones, but nevertheless they can cause death and injury, and result in severe damage to housing and other infrastructure. Their distribution, frequency and severity depend on the potential for warm, humid air masses to combine with much colder and drier air currents (such as the polar jet stream). In a warmer world, tornado occurrence may thus move away from the equator. Predictions of future patterns of intensity cannot yet be made however.

During a tornado, the main form of injury is severe trauma to the head, followed by crush injuries to the chest and other parts of the trunk. Fractures, lacerations and other soft tissue damage are also common. Injuries are often multiple and frequently become infected, leading to sepsis. A survey of casualties following tornadoes in North and South Carolina, USA, in 1979 showed that around 6% were fatalities, 27% hospital cases and 67% cases that were treated and sent home (Glass et al., 1980). In the USA, during the period 1952–1973, 2575 tornadoes occurred, 497 of which caused 3125 deaths. Almost half of these tornadoes caused only one fatality, but 26 of them (around 1%) caused 1180 deaths (Fujita, 1973). For the elderly, risk appeared to increase with age. A strong risk gradient was also observed in relation to the level of physical protection, with risk of death ranging from 3 per thousand for those inside houses, to 23 per thousand for people in cars, to 85 per thousand for people in mobile homes (Glass et al., 1980).

Health impacts of extreme weather events

Freshwater supplies

Availability of fresh water per capita is expected to decline markedly in all developing countries that have high rates of population growth (Kaczmarek et al., 1996). Important regional differences in water scarcity within countries may also occur. Thus in regions where water supplies for local

Box 6.4. Climate change and freshwater supply and quality

Major uncertainties pertain to projections of the potential impact of climate change on regional and local freshwater supplies. The 1996 IPCC assessment therefore provides projections of future availability at the subcontinental scale. Difficulty in predicting the impacts of climate change on freshwater supplies relate to:

- lack of knowledge of how changes in precipitation are related to changes in run-off, water basin budgets, and groundwater availability;
- the fact that the impact of changes in precipitation on run-off and groundwater recharge is non-linear and subject to threshold effects;
- the lack of regional and local specificity of GCM climate change scenarios;
- poor estimation of future changes in climate variability (in particular regarding precipitation extremes);
- uncertainty regarding water resource demand for agriculture, hydroelectric power, and industrial and municipal supply (especially in rapidly urbanizing areas);
- uncertainty regarding the socioeconomic and environmental impacts of water-shortage response measures.

Source: Kaczmarek et al., 1996.

Table 6.4. Estimated water availability (m^3 per year, per capita) for 2050, based on present climate conditions and three transient climate change scenarios (GFDL, UKMO and MPI GCMs). Per capita water availability of less than 1000 m^3 per year is commonly used as a benchmark of water scarcity.

Country	Present climate 1990	Present climate conditions 2050	Climate scenarios range 2050
China	2500	1630	1550–1780
Cyprus	1280	820	620–850
France	4110	3620	2510–2970
Haiti	1700	650	280–840
India	1930	1050	1060–1420
Japan	3210	3060	2940–3470
Kenya	640	170	210–250
Madagascar	3330	710	480–730
Mexico	4270	2100	1740–2010
Peru	1860	880	690–1020
Poland	1470	1250	980–1860
Saudi Arabia	310	80	30–140
South Africa	1320	540	150–500
Spain	3310	3090	1820–2200
Sri Lanka	2500	1520	1440–4900
Thailand	3380	2220	590–3070
Togo	3400	900	550–880
Turkey	3070	1240	700–1910
Ukraine	4050	3480	2830–3990
United Kingdom	2650	2430	2190–2520
Viet Nam	6880	2970	2680–3140

Note: assumptions about population growth are from IPCC IS92a scenario based on World Bank 1991 projections; the climate data are from IPCC climate scenarios from transient model runs. The results show that in all developing countries with a high rate of population growth, future per capita water availability will decrease independently of climate change.

Source: Kaczmarek et al., 1996.

populations are already inadequate, chronic water shortages are anticipated. Further reductions in water availability per capita are anticipated in some countries due to human-induced climate change, although such forecasts are highly uncertain (see Box 6.4). (The health impacts of reduced water availability are discussed in detail in Chapter 4.) Table 6.4 lists projections of the possible impact of climate change on water availability in selected countries (based on projections of population growth and three different climate change scenarios). In arid and semi-arid zones — which are very vulnerable to small changes in temperature and precipitation — climate change, even if only slight, could have major impacts on water supplies (Kaczmarek et al., 1996). The quality of water supplies would be affected by climate change too, particularly in places where water-quality problems (such as pollution and salinity) already occur (Kaczmarek et al., 1996).

Reduced water supplies would also affect human health indirectly; a third of the world's food crops is currently produced by irrigated agriculture, which consumes approximately 70% of the world's fresh water (Serageldin, 1995). Moreover, for countries that depend on fresh water from outside their own borders, any reduction in supplies would mean greater political and economic vulnerability. The significance of water shortages in provoking conflict is discussed on page 143. Many of the world's major river basins are shared between two or more neighbouring countries (Postel, 1992).

The links between water availability, food production, population, economic growth and potential climate change are very complex and far from being understood, however (Kaczmarek et al., 1996). Nevertheless, the uncertainty of the impact of climate change on water supplies, the current unsustainable demand for water resources, and prospective increases in population and industrialization, make sustainable water management policies a priority.

Infectious diseases

In addition to immediate impacts on health, increased frequency of extreme weather events could have indirect impacts on health, including greater incidence of infectious disease, due to factors such as a breakdown in sanitation, lack of clean fresh water, over-crowding among survivors, lack of effective epidemiological monitoring, and collapse of local health care infrastructure.

Floods, for instance, often cause increases in incidence of diseases associated with faecal–oral transmission. Thus in Bolivia, flooding associated with the El Niño of 1983 led to a 70% increase in the incidence of salmonella infections; young children in particular were affected (Telleria, 1986). Similarly, following flooding in Chile, incidence of hepatitis A, typhoid fever and bacillary dysentery rose dramatically (Cabello, 1991). Other examples of such disease outbreaks include an outbreak of leptospirosis following floods in Recife, Brazil in1965, an outbreak of balantidiasis in the USA after a typhoon in 1971, an apparent increase in mild respiratory disease after floods in the Marshall Islands in 1979, a small outbreak of typhoid fever in Mauritius after a cyclone in 1980, and an outbreak of acute hepatitis E after catastrophic floods in 1988 in Khartoum, Sudan (McCarthy et al., 1994).

However, although some information exists on the transmission of certain types of disease following extreme weather events such as floods and storms, little evidence has been collected on the effects of such events on the transmission of vector-borne diseases. Empirical experience has shown, however, that such events essentially act in one of two ways on vector-borne diseases. A proportion or all of the local vector populations may be destroyed. Floods or heavy rains, for example, can destroy or wash out mosquito larvae inhabiting open water. Heavy rainfall, by increasing the water level, may also increase predation on mosquito larvae by fish, thus decreasing vector abundance yet further (Birley, 1993). (However, vector populations may soon re-establish themselves from surviving individuals or by recolonizing the area affected from surrounding populations.) Alternatively, habitat components, such as breeding or resting sites, food plants, or shade trees, may become modified, and new breeding sites for the vectors created (Cotton, 1993). This is seen in south-eastern Australia where epidemics of Ross River virus infection (an arbovirus infection which causes multiple, long-lasting joint inflammation) often occur after heavy rains in the Murray-Darling basin (Nicholls, 1993; Sutherst, 1993). Likewise in Haiti in 1963, after a cyclone, and in Ecuador in 1983 following ENSO-related floods, malaria incidence was observed to increase (Hederra, 1987; Nicholls, 1993).

Habitat changes can defer recolonization by the original species indefinitely, but closely related species may invade an area successfully if the new environmental conditions are favourable for their reproduction and survival. For example, by destroying forest canopies over vast areas, hurricanes may be instrumental in replacing shade-loving mosquito species — at least until trees have regrown — with others that prefer exposure to sunlight. As the vectorial capacity of the original and invading species may differ considerably, the effect of species replacement on disease transmission depends on the particular species involved.

Infectious disease incidence can also be affected by disaster-response strategies. Thus although the construction of embankments and levees can reduce the risk of flooding, it can also affect local water regimes, which can in turn have complex effects on vector-borne diseases. For example, in the flood-plain areas of Bangladesh, increases in malaria incidence are historically associated with reduced flooding and embankment construction (Birley, 1993).

The nature of the link between infectious disease incidence and disasters has been questioned, however. A review of a range of natural disasters during which the US Centers for Disease Control gave assistance showed that none were accompanied by a well-documented major increase in the incidence of *infectious* diseases (Blake, 1989). In some areas, deteriorating social conditions may have produced the underlying vulnerability, while flooding and subsequent contamination of water sources with sewage served as the precipitating event. Seaman, Leivesley & Hogg (1984) have observed that the widespread belief that epidemics of infectious disease frequently follow disasters may stem from the historical association of war, famine and social upheavals with epidemics of smallpox, typhus, plague and dysentery.

Psychosocial problems

Natural disasters including extreme weather events have many psychosocial effects on victims, rescuers, and health and social workers. Since extreme weather events may become more frequent following climate change and/or intensify, understanding of such impacts, and effective public health procedures for dealing with them, should be developed.

Evidently, communities react in different ways to disasters, their response depending on the size and degree of integration of the community, and its previous experience, if any, in dealing with disasters. In the short-term, an external threat such as a disaster may tend to unify a community but, in the longer-term, conflicts can become intensified and community structures weakened, to the extent that those in authority lose prestige and interpersonal conflicts increase (Drabek, 1986).

A number of factors determine the magnitude and duration of psychological symptoms following disasters, including the nature of the experience, the age of individuals exposed, the structure of the local community affected and the availability of psychological care. For example, following the collapse of a dam in 1972 in Buffalo Creek, USA, it was widely perceived that the authorities had been responsible for the collapse of the dam. But in the case of a sudden natural disaster, such perceptions may be absent. In other words, there is no-one to blame. This can help victims to accept its "inevitability" (Titchener & Frederic, 1976). Yet a meta-analysis of the relationship between disasters and subsequent pyschopathology, using data from 52 studies, suggested higher levels of psychological problems in relation to naturally-caused disasters than in relation to those caused at least in part by humans (Rubonis & Bickman, 1991). Yet other studies have shown that the level of psychological effect of a disaster may depend not so much on whether the disaster is natural or human-induced, but rather on the suddenness and unexpectedness of the impact, the intensity and persistence of the experience, the degree of personal and community disruption, and length of exposure to the visual signs of the disaster (Green, 1982). Bereavement, homelessness, and unemployment may also add to the difficulties experienced (Durkin, Khan & Davidson, 1993). Elderly populations may be severely affected by loss of physical assets, particularly if they lived for many years in their home. This can lead to greater adjustment difficulties. Conversely, a young and relatively transient population may be better able to withstand the psychological sequelae of loss or damage to property.

In view of their so-called subjective nature, the psychological symptoms associated with disasters can prove difficult to define and measure. Post-traumatic stress disorder (PTSD) is now recognized as a specific disorder, however. Incidence of PTSD can be very high after traumatic events such as natural disasters (de Girolamo & McFarlane, 1994). Research into the condition has grown in the last fifteen years, although most of it has been undertaken in developed countries.

Many of the major floods that have caused massive loss of human life have occurred in developing countries, particularly in Asia. But owing to the magnitude of the losses and inadequate research facilities, detailed studies of the psychosocial impacts of these disasters have often not been possible. Of the few studies undertaken, however, a short-term follow-up study five months after the 1988 floods in Bangladesh, during which millions of people were left homeless, demonstrated that among a group of 162 children aged 2–9 years, aggressive behaviour and other behavioural disturbances had increased (Durkin, Khan & Davidson, 1993). More work is needed to determine the duration of such behavioural changes.

Studies of major floods in developed countries have shown that those whose homes are inundated, may suffer long-term effects on mental health. For instance, the Buffalo Creek dam collapse resulted in 125 deaths and left 4000 homeless (Titchener & Frederic, 1976). Traumatic neurotic reactions were observed in 80% of survivors and some experienced persistent feelings of unresolved grief, survivor shame, impotent rage and hopelessness. Developmental problems were observed for more than two years after the disaster in over 90% of the children interviewed. A 14-year follow-up study of 193 individuals exposed to the Buffalo Creek disaster showed that 25% of survivors continued to suffer from PTSD (Green et al., 1992). The same study found that 37% of the children studied, aged between 2 and 15 years had PTSD (Green et al., 1991). Of all the individuals included in the study, major depression was being experienced by 19.3%, and a generalized anxiety disorder by 17.6%. A close association was observed between major depression and PTSD; after the disaster, PTSD had occurred in nearly 60% of the sample and major depression in 36% of the sample. Interpretation is complicated by the fact that the groups studied represented only 39% of the living survivors. Nevertheless this research suggests that long-term psychiatric effects may continue to be a problem many years after a disaster has occurred.

Other studies have suggested a shorter duration of psychological dysfunction. For example, a follow-up of individuals who experienced a cyclone in Darwin, Australia, showed that 14 months after the event, the level of psychological dysfunction had returned to that of an unaffected comparable population (Parker, 1977). The severity of psychological disorders and their persistence apparently depend on the nature and gravity of a disaster and the socioeconomic conditions of the community affected.

The psychological effects of disasters may have a considerable impact on the health care system. For example, for a year following a flood in Bristol, UK, in 1968, during which 3000 homes were flooded and one individual died, the number of visits to doctors showed an increase of 53%

(Bennet, 1970). A similar pattern was noted following a flood in Brisbane, Australia, in 1974 (Abrahams et al., 1976).

Environmental factors and displaced persons

The term "environmental refugees" is frequently used but not recognized officially. In its 1985 report, UNEP defined environmental refugees as "people who have been forced to leave their traditional habitat, temporarily or permanently, because of a marked environmental disruption — either natural or human-induced — that jeopardized their existence and/or seriously affected their quality of life" (El-Hinnawi, 1985). The Office of the United Nations High Commissioner for Refugees defines refugees as persons deemed to have left their country for fear of persecution due to political, religious, ethnic or other reasons. International law accords such "official" refugees special status and protection.

Cumulative environmental degradation, be it in the form of soil erosion, deforestation, desertification or water shortage is widespread and often associated with both population growth and population movement. However, environmental degradation can also occur at very low population densities and in populations which are not growing. The impacts of environmental degradation obviously vary enormously and are mediated through social, economic and political structures. Differentiating between population movement triggered primarily by environmental factors, and population movement that is mainly attributable to social, political or economic causes, can therefore be difficult (Zaba & Clarke, 1994). Bangladesh illustrates this well. Populations in this country have been shown to migrate to cities not because they are fleeing the impacts of a disaster, but because, a disaster having occurred, they lack the capacity and means to re-establish their communities (Kibreab, 1994). Unfortunately, interdisciplinary research into such issues is lacking.

But despite difficulties concerning definition, demographic data and environmental data, attempts have been made to analyse and quantify the refugee problem (see, for example, Westing, 1992; Myers & Kent, 1995). It has been estimated that there are around 18 million officially recognized (i.e. political, religious or ethnic) refugees, and around 10 million environmental refugees, half of whom are in sub-Saharan Africa (Westing, 1992). Estimates made by Myers and Kent (1995) are even higher. Thus they have estimated that in 1994 there were 22 million officially recognized refugees and 25 million environmental refugees. But whichever set of figures is considered to be most credible, the global refugee problem is obviously immense. Indeed, more than 30 countries have generated more than 100 000 refugees each. Some of the countries to which refugees have fled are very poor. For instance, Malawi, is among the 12 poorest countries in the world. Yet one in nine of its population is a refugee; 800 000 of the refugees in Malawi fled there from Mozambique (Myers, 1994b).

WHO (1990b) has pointed out that climate change could contribute to increased population movement via:

- declining agricultural productivity;
- managed or unmanaged retreat from land which is vulnerable to sea level rise (see Chapter 7);
- temporary displacement following natural disasters such as floods, wind storms and drought.

Historically, declining agricultural productivity has been a major trigger for population movement. In recent decades, for example, famines following extended drought have led to large population movements in the Sahel (see also Box 6.2). Political factors may, however, ultimately have become more significant than those relating to climate. In areas where low-income populations are dependent on subsistence agriculture, particularly dryland, non-irrigated agriculture in arid and semi-arid regions, any further decreases in productivity due to changes in the local climate regime (see Chapter 5), reduced availability of fresh water, or more frequent extreme weather events, would doubtless lead to further population movement.

The depopulation pattern of coastal zones affected by subsidence provides an analogue for predicting population movement resulting from sea level rise and for guiding preventative action (see also Chapter 7). In fringe areas of densely-populated land areas especially, coastal populations tend — for cultural and economic reasons — to resist moving over long distances. Adaptive measures are therefore fairly acceptable to them. Inhabitants of low-lying islands, however, do not always have that choice, and unless managed transmigration schemes are put in place in good time, island populations can become environmental refugee populations.

If extreme weather events become more common, further temporary displacement of populations — into emergency camps, for instance — can be expected. Crowding in such camps often has negative health impacts in addition to the more immediate health impacts, namely deaths and injuries, of disasters. For instance, infectious diseases often spread rapidly due to poor sanitary conditions and lack of adequate food.

Individuals uprooted by environmental pressures and disasters may also suffer adverse health effects simply because they are highly exposed to the elements. The effects of this exposure, combined with problems commonly experienced by refugees and displaced populations such as injury and loss of possessions, potentiate further psychological and physical stress. Long-term effects on social values and cultures may also be experienced. Increased susceptibility to infectious diseases may occur too, since environmental conditions, including types of pathogen, may differ from those of the area that was left. Refugees may also carry diseases from their country of origin into their new environment, although, in fact, infectious disease incidence has often been shown to be linked to socioeconomic factors rather than to recent population movement from endemic areas. This has been seen in connection with tuberculosis in the UK, for example (Bhatti et al., 1995; Mangtani et al., 1995). Furthermore, a study in Canada has shown that non-indigenous populations are less likely to be screened adequately and treated for serious disease than the indigenous population, and less likely than the indigenous population to take advantage of preventive medical services (Anderson et al., 1992).

Clearly, if climate change results in greater frequency of extreme weather events, additional resources for dealing with refugees and displaced populations will have to be mobilized.

Environmental factors and conflict

Environmental degradation both contributes to and results from conflict. Although seldom the only cause of major conflict within or among countries, it can be an important contributory factor or even a catalyst (WCED, 1987). Climate change could exacerbate environmental problems, including resource depletion, thereby increasing future conflict.

More than 40% of the world's principal river basins are shared by two or more countries. Hostilities over water rights have occurred already in connection with the Rivers Jordan, Euphrates and Mekong (Postel, 1992). In the Middle East, especially, water rights are an important issue for countries that have high population growth rates and that rely heavily on irrigation. Climate change could therefore increase tension over water resources in this region. Elsewhere, access to fresh water may be likewise complicated by conflict concerning rights to water in shared river basins and to aquifers that cross national boundaries (Kaczmarek et al., 1996).

The growing problem of environmental refugees or environmentally displaced persons has been identified as a potential factor in such future conflicts (WCED, 1987). The impact of climate change on population movement is highly uncertain, however. Some idea, though, can be gained from current situations. For instance, population movement stemming from high population density and shortage of land has been seen to create serious tension between neighbouring countries such as Bangladesh and India (Myers, 1989; 1994a). Around 15 million migrants from Bangladesh and their descendants live in neighbouring areas of India. The majority moved to India because population density is very high in Bangladesh (around 7 people/km^2), and available cropland amounts to a mere 0.08 hectare per capita. The influx of migrants from Bangladesh has created considerable tension, particularly in Assam, where in 1983, local tribespeople massacred immigrant Bengalis (Homer-Dixon, Boutwell & Rathjens, 1993). The impact of sea level rise on a country already suffering chronic land shortages could lead to further population movement and further conflict.

Increased civil unrest can be expected to result from climate change if the latter causes significant reductions in food production and displacement of populations. In the past, governments have sometimes responded in such cases by increasing repression and military expenditure, which led to more poverty, hence increasing the disaster vulnerability of some population groups. King and Elliott (1993) identify this vicious circle as one of the major threats of demographic "entrapment". Poverty and social unrest prevent populations from remaining well within the carrying capacity limits of their land and thus maintain their dependency on external aid programmes. Any analysis of the potential impacts of climate change must therefore examine sustainability in the light of future population density and future agricultural production. Conflict over food may be avoidable to some extent by the rapid development of food import and export industries.

Disaster mitigation

Populations all over the world will probably become more vulnerable to extreme weather events and climate change impacts. Data on recent natural disasters has revealed that this increasing vulnerability is attributable to a combination of rapid population growth, unplanned urban settlement (particularly in coastal areas), and persistent poverty (IFRC, 1996). The major socioeconomic impacts of extreme weather events, resulting from property damage, replacement costs, clean-up expenses, unemployment and the reduced socioeconomic viability of the communities affected, may thus represent a heavy additional burden. Public health infrastructure may also be affected if resources for its maintenance are diverted to disaster recovery.

Future projections of land-use changes indicate that in many countries the poorest population sectors will congregate increasingly on the land that is most vulnerable to the impacts of natural disasters. Thus although the exact role of climate change in the changing patterns of natural disasters remains uncertain, these countries should, as a priority, formulate national disaster-response strategies as part of their sustainable development planning (Bruce, 1994). Such strategies should include:

- efforts to ensure that buildings and urban and rural infrastructures are built to withstand extreme weather events;
- land-use planning and zoning to maintain strict control over any development in high-risk zones and to discourage human settlement in such zones;
- improved warning and preparedness systems so that loss of life and damage to property and food supplies are minimized in disaster situations;
- efforts to match demographic policies (pertaining to migration, settlements, family planning) with future agricultural and industrial carrying capacity;
- prevention of environmental degradation.

International cooperation to reduce the human impact of natural disasters may be undertaken within the framework of the UN's International Decade for Natural Disaster Reduction (IDNDR Secretariat, 1994). The IDNDR focuses on the prevention of disasters rather than relief operations, and stresses the importance of disaster early warning systems. IDNDR intends to promote strengthening of national and local capacity to cope with disasters, particularly with respect to vulnerable groups and communities.

Although individual countries must bear primary responsibility for protecting their populations and infrastructure from the impact of natural disasters, the international community should mobilize existing resources, including scientific and technological means, so that relief operations can be initiated as soon as disasters occur. That said, it is generally accepted that human and material investment in prevention and (preparedness) is more cost-effective than relief operations.

The average impact of new, more frequent, more severe natural disasters that might occur regionally as a consequence of climate change can be managed with foresight and adoption of adaptive measures. Given the many and great uncertainties pertaining to prediction of climate change impacts, the most appropriately adapted defence systems will be those that are sufficiently robust to withstand a range of possible scenarios. This will of course require greater investment in infrastructure and preparedness institutions than is currently made (Downing, Olsthoorn & Tol, 1996).

Chapter 7

Sea level rise

Past and future sea level rise

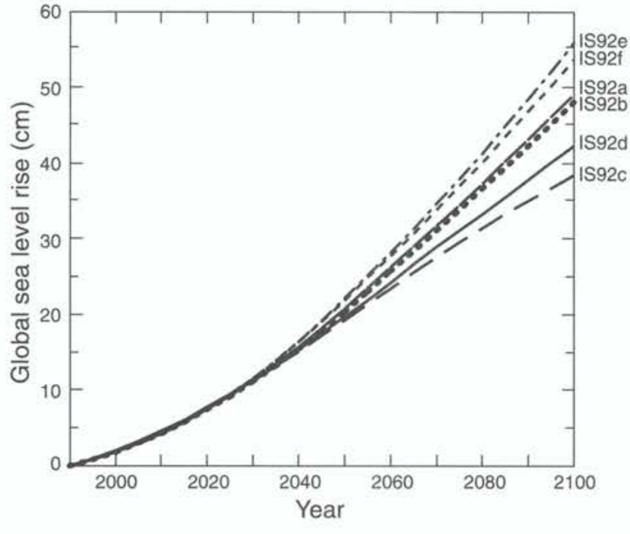
Coastal zones are of great importance to human welfare. Throughout history, human settlements have concentrated along coastlines and rivers, and in alluvial plains, to take advantage of the opportunities they provide for agriculture, fisheries and trade. More than half of the world's population now lives within 60 km of the sea and the average growth rate of this coastal population is higher than that of the global population (Holligan & de Boois, 1993; WCC'93, 1994). Additionally, sixteen of the twenty-three cities whose populations are expected to individually exceed 10 million inhabitants by the year 2000 are located in coastal zones. Sea level rise and changes in the frequency and severity of extreme weather events are likely to be the most significant climate change phenomena to occur in these zones.

During the past 18 000 years, global sea level has risen by about 100 m in total. But most of that rise had already occurred by the time the last ice age ended, about 10 000 years ago. During the past century, sea level has risen by around 18 cm, or an average of 1–2.5 mm/year (Warrick et al., 1996). Global mean temperature increases contribute to sea level rise via several mechanisms, the most notable being thermal expansion of the oceans, followed by melting of mountain glaciers and polar ice sheets (see Chapter 2). Changes in sea level also occur due to natural dynamic effects such as changes in ocean circulation and wind and pressure patterns. Variations in these effects partly account for regional variations in sea level rise.

Shorelines themselves are not static. Natural geological processes (such as tectonic shift, glacial rebound, sediment compaction, and subsidence) as well as human activities (such as extraction of oil, gas or water, and sediment) can cause coastal land to move relative to the level of the sea. For example, the removal of groundwater can greatly increase the rate of local subsidence. Since the late 1920s and 1930s, a number of large coastal cities have subsided due to excessive pumping of groundwater, with a maximum subsidence of 5 m in Tokyo, Japan, 2.8 m in Shanghai, China, and 2.8 m in Osaka, Japan (Nicholls, 1995a). Such problems continue in coastal cities such as Tianjin in China and Jakarta in Indonesia (Han, Hou & Wu, 1995; Nicholls, Mimura & Topping, 1995). Local changes in land and sea levels are obviously independent of those due to global sea level rise. But cities or coastal zones currently experiencing difficulty in coping with relative sea level rise, will be especially vulnerable to future global sea level rise.

The "best" estimate of current ocean and climate models is that sea level will have risen by around half a metre by the year 2100 and will continue to rise thereafter, even if global greenhouse gas emissions are stabilized (Wigley, 1995b). The current best estimate thus predicts a rate of sea level rise, for the period between now and 2100, that is two to three times greater than that of the past 100 years. Figure 7.1 illustrates the wide range of projections of future sea level rise.The time-lag in the response of the oceans to atmospheric warming, and the rate of melting of the fringes of polar ice sheets (and the possible, although unlikely collapse of the West Antarctic ice

Fig. 7.1. Projected global mean sea level rise from 1990 to 2100 for the full set of IS92 emission scenarios. A climate sensitivity of 2.5°C and mid-value ice melt parameters are assumed.



Source: IPCC, 1996a.

sheet; see Chapter 2), constitute major uncertainties in these assessments. Furthermore, local sea level changes could differ substantially from global mean estimates due to shifting ocean currents and trade winds which can force water volumes up along coastlines.

Effects of sea level rise on ecosystems

Coastal zones are the result of dynamic interaction between land and sea, which varies in accordance with the mineral structures and contours of the surrounding land, relative rates of sedimentation, and erosion caused by ocean currents, waves, tides and rivers. This interaction must be taken into account when modelling the impacts of projected sea level rise on coastal zones. Simply shifting the land–sea boundary by an amount corresponding to the projected vertical increase in sea level would be equivalent to ignoring it, and any predicted impacts would be oversimplified (Bijlsma et al., 1996). Similarly, the varied and diverse characteristics of ecosystems that are supported by coastal zones, such as coral reefs, mangroves and salt marshes, must be incorporated into sea level rise models. This is necessary because these ecosystems respond to and modify a range of biogeophysical processes that impact on coastlines, thereby creating their own dynamic effect.

One of the most likely impacts of sea level rise on coastal zones will be increased erosion. Some coastal erosion is evidently due to natural processes. But the effects of these are often amplified as a result of human activities such as sediment removal. Coastal erosion can have severe consequences and lead to loss of natural protective features such as dunes and mangroves (Snedaker, 1984). Of the world's coastlines, about 20% are sandy, and of these, 70% have retreated during the past 100 years (Bird, 1985, 1993). Observed sea level rise may be only one possible contributory factor. It is clear, however, that increased sea level rise would exacerbate coastal erosion in many areas, particularly if local environmental destruction or modification has occurred already (Bijlsma et al. 1996). Models of the effect of sea level rise on sandy shorelines are being developed but more research is needed (SCOR Working Group 89, 1991).

Climate change could also have particularly adverse impacts on coastal wetlands, which include marshes and mangroves, and on coral reefs. Coastal wetlands have many important functions. For instance, they serve as breeding and nursery areas for fish, and as such are often of considerable economic importance. They also filter nitrogen and phosphorus and store carbon, thereby contributing to maintenance of a healthy, clean environment. This diversity of function means that the physical, biological and chemical mechanisms of coastal wetlands operate according to a delicate balance. This is illustrated, for example, by the complex process of accretion of sediment and submergence (Stevenson, Ward & Kearney, 1986; Parkinson et al., 1994). The impacts of sea level rise on wetlands will vary, depending on particular factors such as tidal range, sediment input and direct destruction. In many cases, the negative impacts will be additional to those that have resulted from previous human activity. In the Mississippi River Delta, in the USA, for instance, the sediment and freshwater systems necessary for sustaining the local wetlands have been disrupted by the development of canals, diversions, dikes and levees. Sea level rise could harm these ecosystems yet further.

Over 900 000 km^2 of ecologically and economically valuable coastal wetlands are estimated to remain worldwide. Over half of these would be threatened by a 1 m rise in sea level over the next 100 years (Hoozemans et al., 1993). The most severely threatened coastal wetlands are found along coasts of the Mediterranean and the USA, along the African Atlantic coast and the Australian and Papua New Guinea coasts, and along the coast of east Asia (Hoozemans et al., 1993). But as coastal wetlands are now being reclaimed in many parts of the world, it remains uncertain what wetlands will remain to be adversely affected by sea level rise.

In common with coastal wetlands, coral reefs have a number of functions, many of which are important for human survival and development. These include protection of coastlines and provision of habitat and breeding grounds for marine life. Additionally, they contain the highest species biodiversity of any marine ecosystem, with very large numbers of species found in small areas. The potential "vertical" growth rate of coral — which consists of symbiotic life forms composed of tiny animal and plant organisms — ranges from around 1–10 mm per year, and should therefore be able to keep pace with predicted sea level rise, assuming that no other factors affect coral growth. Even so, overfishing, mining, pollution, and sedimentation, ensure that coral reefs continue to be among the world's most threatened ecosystems.

Global warming could damage coral directly by increasing "coral bleaching" (Goreau & Hayes, 1994). Short-term warm-season increases in sea surface temperatures of only 1°C are sufficient to cause this phenomenon. Therefore, sustained temperature increases of 3–4°C above long-term maxima over a six-month period, which could occur following climate change, might cause the death of extensive areas of coral. Increased incidence of coral bleaching observed during the past few decades is consistent with worldwide ocean warming, although other factors may also have contributed (IPCC, 1992). Recovery from bleaching can take considerable time. In sites as diverse as Indonesia, the Galapagos Islands and eastern Panama, coral systems underwent severe bleaching following ocean warming during an El Niño event in 1982–1983; recovery to date has been minimal. Sustained recovery could take centuries (Glynn, 1993). Coral reefs could also be damaged by increased levels of ultraviolet radiation associated with stratospheric ozone depletion (Gleason & Wellington, 1993).

Recent studies on the impact of sea level rise on atolls, which take into account the potential dynamic responses of coral to sea level rise are more optimistic than earlier assessments. Coral reefs nevertheless remain very vulnerable to this particular aspect of climate change (Bijlsma et al. 1996).

Assessment of vulnerability of coastal zones to sea level rise

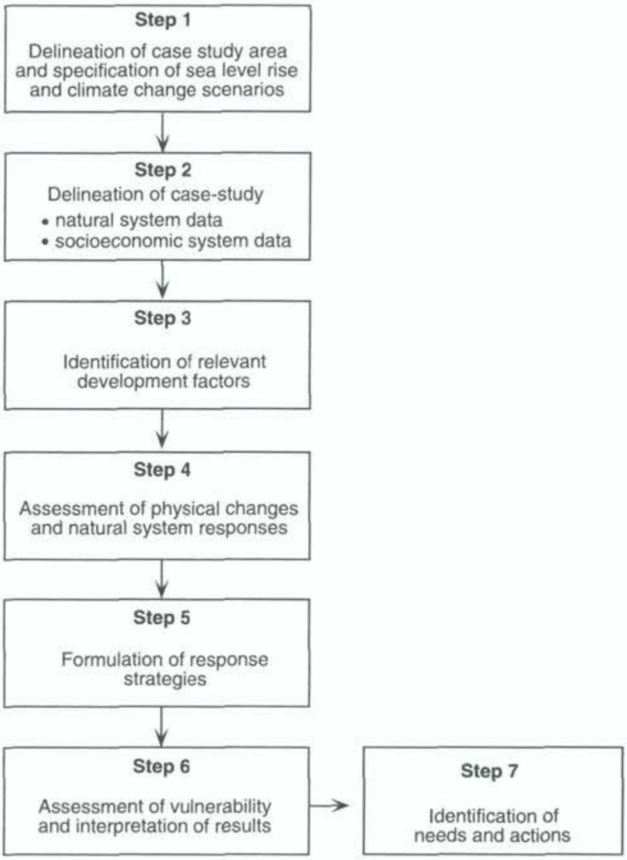
The Intergovernmental Panel on Climate Change (IPCC) has developed a "Common Methodology" for assessing the vulnerability of coastal zones to sea level rise (see Fig. 7.2) (IPCC CZMS, 1992). It encompasses the reference or present situation relating to relative sea levels, details concerning factors such as local tides and the frequency of storm surges, and IPCC's 1990 low and high estimates of projected sea level rise (i.e. 0.3 m and 1 m, respectively, by the year 2100). Adjustments are made for specific areas for local subsidence or uplift, local variability in storm surges, and other local circumstances, if these are known. The methodology has been used widely to identify populations and resources at risk, and to assess the costs of potential responses. But experience in using the IPCC Common Methodology now indicates that a broader approach should be taken to the issue of vulnerability, so that cultural, community and aesthetic values are taken into account (Bijlsma et al. 1996). For example, since the IPCC Common Methodology adopts a market-oriented approach, it does not allow for adequate assessment of the impacts of sea level rise on the subsistence economies of small communities. Methodologies which address such questions are being developed, however (see, for example, Yamada et al., 1995).

The first step in applying the IPCC Common Methodology consists of assessing the *susceptibility* of a coastal zone to the biogeophysical effects of climate change and sea level rise. This *susceptibility* is conditioned by the *resilience* of the local systems, which is greatly influenced by factors such as population pressure and rates of economic development. The *vulnerability* of a population is defined as the "degree of incapability to cope with the consequences of an acceleration in sea level rise and other effects of climate change". It is determined by socioeconomic factors, including socioeconomic conditions (IPCC CZMS, 1992). Assessment of vulnerability therefore includes:

- assessment of the physical, ecological and socioeconomic impacts of sea level rise;
- assessment of the socioeconomic development determinants of vulnerability;
- elucidation of how potential responses could reduce vulnerability, or mitigate impacts, or enable a population to adapt to impacts;
- evaluation of national capacity to implement response measures.

This type of approach assumes linear interactions between coastal systems and physical and human responses. This is of course a simplification, and complex non-linear interactions should therefore form a topic of future research. Moreover, the impacts of sea level rise on human health are not addressed specifically by this methodology, although populations at risk of flooding are considered. Future work on vulnerability analysis should therefore be expanded to examine the range of potential impacts on population health. Meanwhile, analysis using the IPCC Common Methodology can provide policy-makers with indicative estimates of the vulnerability of coastal zones, enabling a preliminary analysis to be made of possible response strategies.

Fig. 7.2. Stepwise approach for vulnerability analysis: "The Common Methodology"



Source: IPCC CZMS, 1992.

Global vulnerability assessment

A model has also been developed to assess *global* vulnerability to sea level rise that is similar to the IPCC Common Methodology (Hoozemans et al., 1993). The global vulnerability assessment (GVA) model incorporates a variety of sea level rise scenarios including a scenario involving a global 50 cm rise in sea level by the year 2100. It also incorporates a more flexible method for estimating the probability of flooding and takes possible protection measures into account (Baarse, 1995). The model predicts the geographic distribution of risk areas and identifies corresponding numbers of people at risk. The number of people "at risk" is defined by the model as the arithmetical product of the number of people living in an area and the probability of that area being subjected to flooding during one year. For example, if 100 million people live within the 1 in 1000 year risk zone, 100 000 people would be considered to be at risk.

Under present climate and sea level conditions, 46 million people on average experience flooding due to storm surge every year. Worldwide, an estimated 200 million people currently live in zones where the risk of flooding due to storm surge is greater than 1 in 1000 years (Hoozemans et al., 1993). Using 1990 population figures, Baarse (1995) has estimated that if coastal protection systems are not strengthened, the number of people at risk will double if sea level rises by 50 cm (i.e. 92 million people/year), and almost triple if it rises by 1 m (i.e. 118 million people/year). Baarse (1995) has also estimated the number of people for whom the probability of experiencing flooding is greater than once a year. Thus he estimates that a 50 cm rise in sea level by 2100 would place 80 million people at risk of being flooded more than once a year.

Calculations of the number of people at risk are highly sensitive to assumptions about the *level* of protection. For example, in the Netherlands, assuming the present level of protection is maintained, 24 000 people would be at risk following a 1 m rise in sea level. But if it is assumed that no maintenance or improvement of coastal protection systems will be undertaken in the Netherlands during the next hundred years, over 3.7 million people would be at risk (Nicholls, 1995b). In terms of people at risk as a percentage of the total population, small island states in the Pacific Ocean such as Kiribati, Samoa and Tonga are most at risk, followed by the island states in the Indian Ocean, and countries bordering the Indian Ocean, such as Bangladesh and Myanmar. The global population at risk can be estimated by summing the populations at risk in individual risk zones or by cluster analysis (Hoozemans et al., 1993; Baarse, 1995).

Models for estimating global vulnerability to sea level rise must also take population growth in coastal zones into account since this could greatly exacerbate the impacts of sea level rise. Obviously, if populations in coastal zones increase, a greater number of people will be vulnerable. Furthermore, the zones themselves will be more vulnerable because of increased pressure on their natural resources. Very high population growth rates are anticipated for the African Atlantic coast and in the Gulf States. Population growth on the African coast is of concern because local resources for coastal protection are inadequate. The same may apply to large populations at risk along the Indian Ocean coast, especially in Bangladesh and India, and in east Asia, notably in China. Other countries with large coastal populations at risk include Viet Nam and Mozambique. In the developed world, densely populated coastal centres account for about 15% of the total global population at risk. However, their relatively safe defence systems mean that in real terms their populations are less at risk. Overall, population growth and projected sea level rise appear to be of comparable importance in terms of their contribution to the number of people at risk.

In addition to effects on human populations, global vulnerability models have also been used to assess the effect of sea level rise on loss of wetlands, rice production, protection costs and capital coastal infrastructure assets (Hoozemans et al., 1993; Baarse, 1995).

Overview of country studies

In addition to the "top-down" approach of GVA, a "bottom-up" approach that aggregates results from local area and country studies, has also been undertaken. The results from 23 country case studies are summarized in Table 7.1. They illustrate clearly the considerable variation in vulnerability to sea level rise between countries, and underline the message that climate change will impact most severely on coastal systems that are already under stress.

In these case studies, the number of people who would be affected is defined as the number of people living in a risk zone which, in the absence of any coastal protection, will be subject to inundation or flooding at least once per 100 years, if sea level rises by 1 m. (In the GVA model a

Table 7.1. Summary of results of country case studies. Results assume an existing rate of development, 1 m rise in sea level, and no protection measures (i.e. no human response), whereas adaptation assumes protection except in areas with low population density.

Country	People affected		Capital value at loss		Land at loss		Wet-land at loss	Adaptation/ protection costs	
	no. 1000s	% total	million US$[a]	% GNP	km^2	% total	km^2	million US$[a]	% GNP
Antigua[b]	38	50	-	-	5	1.0	3	71	0.32
Argentina	-	-	>5000[f]	>5	3400	0.1	1100	>1800	>0.02
Bangladesh	71000	60	-	-	25000	17.5	5800	>1000[h]	>0.06
Belize	70	35	-	-	1900	8.4	-	-	-
Benin[c]	1350	25	118	12	230	0.2	85	>400[i]	>0.41
China	72000	7	-	-	35000	-	-	-	-
Egypt	4700	9	59000	204	5800	1.0	-	13100[j]	0.45
Guyana	600	80	4000	1115	2400	1.1	500	200	0.26
India	7100[e]	1	-	-	5800	0.4	-	-	-
Japan	15400	15	849000	72	2300	0.6	-	>156000	>0.12
Kiribati[b]	9	100	2	8	4	12.5	-	3	0.10
Malaysia	-	-	-	-	7000	2.1	6000	-	-
Marshall Is.[b]	20	100	160	324	9	80	-	>360	>7.04
Mauritius[d]	3	<1	-	-	5	0.3	-	-	-
Netherlands	10000	67	186000	69	2165	5.9	642	12300	0.05
Nigeria	3200[e]	4	17000[f]	52	18600	2.0	16000	>1400	>0.04
Poland	240	1	22000	24	1700	0.5	36	1400	0.02
Senegal	110[e]	>1	>500[f]	>12	6100	3.1	6000	>1000	>0.21
St Kitts-Nevis[b]	-	-	-	-	1	1.4	1	50	2.65
Tonga[b]	30	47	-	-	7	2.9	-	-	-
Uruguay	13[e]	<1	1700[f]	26	96	0.1	23	>1000	>0.12
USA	-	-	-	-	31600[g]	0.3	17000	>156000	>0.03
Venezuela	56[e]	<1	330[f]	1	5700	0.6	5600	>1600	>0.03

[a] Costs have been adjusted to reflect 1990 US$.
[b] Minimum estimates — incomplete national coverage.
[c] Precise year for financial values not given — assumed to be 1992.
[d] Results are interpolated linearly from results for a 2 m sea level rise scenario.
[e] Minimum estimates — number reflects estimated people displaced.
[f] Minimum estimates — capital values at loss does not include ports.
[g] Best estimate is that 20 000 km^2 of dry land are lost but about 5400 km^2 are converted to coastal wetlands
[h] Adaptation only provides protection against a 1-in-20 year event.
[i] Adaptation costs are extrapolated linearly from a 0.5 m sea level rise scenario.
[j] Adaptation costs include 30-year development scenarios.

Sources: Peerbolte et al., 1991; Titus et al., 1991; Delft Hydraulics et al., 1992; Hothus et al., 1992; Pluijm et al., 1992; Woodroff & McLean, 1992; Bilan, 1993; Kahn & Sturm, 1993; Mimura et al., 1993; Pernetta & Elder, 1993; Cambers, 1994; Fifita et al., 1994; Jogoo, 1994; Pachauri, 1994; Adam, 1995; Dennis et al., 1995; Dennis, Niang-Diop & Nicholls, 1995; French et al., 1995; Han et al., 1995; Huq et al., 1995; Midun & Lee, 1995; Nicholls & Leatherman, 1995a; Volonté & Arismendi, 1995; Volonté & Nicholls, 1995; Bijlsma et al., 1996.

risk zone subject to flooding once per 1000 years is used.) According to this assessment, the vast majority of people who would be affected live in one of two countries: China (72 million) or Bangladesh (71 million) (Nicholls, 1995b). The percentage of the population of each country studied that would be affected varies from 0.3% for Venezuela, to 100% for Kiribati and the Marshall Islands. By comparison, the GVA model underestimates the numbers affected for Bangladesh, China and Japan because the assumptions upon which it is based are simpler. For example, the GVA model does not incorporate the increased "run-up" of tsunamis for Japan, or changes in river flow for Bangladesh.

The experience of individual countries in coastal protection should also of course be taken into account when assessing national vulnerability. For instance, the Netherlands has considerable experience in establishing coastal protection against flooding and may therefore be less vulnerable than would initially appear. Bangladesh, on the other hand, has much less experience in coastal protection, far fewer resources, and a much higher rate of population growth, all of which increase its vulnerability.

Regional impacts of sea level rise

The regional impacts of sea level rise may usefully be considered as affecting three main types of geographical area: small islands, deltas, and continental or large island shorelines. The following discussion focuses on the first two categories because of their greater vulnerability. Unless indicated otherwise, current population levels and sea level rise scenarios based on a high estimate, namely a 1 m rise in sea level by the year 2100, are assumed.

Small islands

Sea level rise represents a serious risk for populations of small islands because little land is available for retreat, and alternative sources of natural resources such as fresh water generally unavailable. In many cases, local environmental factors, such as uncontrolled coastal development and mining of sand and coral are increasing this vulnerability. Impacts are likely to differ markedly between islands, depending on the presence or absence of natural shore protection, the island's location within or outside a storm belt, and whether or not the island is attached to a rock platform.

Many small island states could suffer the effects of sea level rise, but those that have been identified as particularly at risk include the Maldives, the Marshall Islands, Kiribati, and Tonga (see Box 7.1) (Pernetta, 1992). The Marshall Islands, for example, comprise 29 atolls and five islands with an average elevation of less than 2.4 m. A study of Majuro atoll, which is the location of the islands' capital, calculated that protection against a 0.3 m rise in sea level would cost 1.5–3 times the islands' current GNP (Holthus et al., 1992). In the case of Tongatapu Island, which has a population of 67 000 (two-thirds of the total population of Tonga, of which it is part), a 1 m rise in sea level would inundate the homes of 10% of the population (Fifita et al., 1994). Indeed, in 1982, a tropical cyclone flooded 23 km^2 of the island, affecting one-third of its population. The combined impact of a 1 m rise in sea level and a similar cyclone would affect the homes of 45% of the island's current population.

Box 7.1. The Maldives

The Maldives are a group of 1190 small islands in the Indian Ocean, 202 of which are inhabited. With a total land area of 300 km^2, most of the islands stand no higher than 1 m above mean sea level and none is more than 3 m above mean sea level. The Maldives already experience serious flooding due to swells generated by distant storms.

The islands are founded on coral sand which is easily eroded. The surrounding coral reefs have been degraded by local human activities and it is therefore unlikely that their growth rates would keep pace with projected rises in sea level. The reefs have also been damaged by coral bleaching, due to increased ocean temperatures.

The Maldives are typical of many of the small-island states in the Pacific and Indian Oceans in that they have a high rate of population growth (an average of 3%) and high population density. For example, Male, the capital island, is only 1700 m long and 700 m wide, but is home to 56 000 people. During the dry season, demands on the water supply are sometimes so high that local groundwater becomes contaminated with salt water. In fact, several factors, including population growth, have combined to reduce groundwater supply dramatically and to such an extent that it may soon be depleted totally. Even under present conditions the island's water supply is often contaminated with faecal pathogens due to poor waste disposal management. Furthermore, the cost of supplying desalinated water to the whole population exceeds the Maldives' current annual national export earnings.

The impacts of sea level rise on the islands' water supply systems could accordingly have particularly adverse consequences — both in terms of resource supply and financial cost.

Source: Pernetta, 1992.

Deltas

Deltas are often economically valuable as areas of industrial activity or high agricultural productivity. For example, in China, commercial activities in coastal zone deltas account for around 25% of GNP. Many deltas are also heavily populated (Fig. 7.3). Because they are often low-lying, many of them would be particularly liable to flooding in the event of sea level rise (Nicholls & Leatherman, 1995a). Furthermore, many of them are already threatened due to poor resource management and destruction of surrounding habitat (Bijlsma et al., 1996). In some cases, the construction of dams and other structures to prevent flooding has reduced sedimentation and accelerated local erosion and subsidence. Erosion and subsidence have also been exacerbated by groundwater withdrawal, as has been seen in Shanghai and Tianjin in China. Protection from sea level rise would cost several hundred million dollars for their populations of 13 and 7 million people respectively (Han, Hou & Wu, 1995; Wang et al., 1995).

The most vulnerable deltas probably include the Ganges-Brahmaputra Delta in Bangladesh, the Nile Delta in Egypt (see Boxes 7.2 and 7.3), and the Mahamadi and the Ganges Deltas in West Bengal. In West Bengal, sea level rise of 1 m would result in inundation of about 1700 km^2 —

Box 7.2. Bangladesh

The delta created by the Ganges, the Brahmaputra and the Jamuna Rivers, comprises 80% of the land area of Bangladesh. It experiences an annual throughput of around 970 km^3 of water and more than 1000 million tons of sediment.

Bangladesh is economically disadvantaged, with high rates of infant and maternal mortality. It is also one of the most densely populated countries in the world. More than 110 million people live in an area of 144 000 km^2. Population pressure is so high that many people are obliged to live on land that is highly vulnerable to flooding. Recent studies show that up to 17% of Bangladesh's land could become submerged if sea level rises by 1 m, and about 11 million people displaced from their homes. Local subsidence rates may exceed 1 cm per year, and would increase the impact of sea level rise. Since population density is so high, planned retreat and resettlement may not be a practical response to sea level rise.

An average of 1.5 tropical cyclones batter Bangladesh annually and the effects of storm surges sometimes reach as far as 200 km inland. During the last two centuries, cyclones have caused about 800 000 deaths in Bangladesh: for instance, around 300 000 lives were lost in 1970, and a further 140 000 in 1991. A rise in sea level would cause the frequency and severity of the storm surges of such cyclones to increase. Bangladesh is also subject to inland flooding associated with the monsoon, and catastrophic floods caused, as in 1988, by excessive run-off from the Himalayas due to early melting of glaciers and snow. Climate change could therefore have a variety of adverse impacts on Bangladesh. In addition, the construction of flood defence systems may have had a detrimental impact on coastlines.

In the west of the delta, where monsoon and dry season river flows have been reduced following natural and human-induced changes upstream, saltwater intrusion could affect food production as sea level rise becomes significant. This is likely to occur in the dry season, when rainfall is not sufficient to prevent severe salinization of soils.

Due to land–sea dynamics, permanent protection against sea level rise may be too costly or environmentally disruptive for many of Bangladesh's coastal zones. Additionally, since periodic flooding is required to ensure that land subsidence is counteracted by sedimentation, the construction of levees along rivers would not constitute an appropriate means of land conservation or protection.

Sources: Milliman & Meade, 1983; Milliman et al., 1989; Warrick & Rahman, 1992; Brammer, 1993; World Bank, 1993; Asaduzzaman, 1994; Huq, Ali & Rahman, 1995; Nicholls, Mimura & Topping, 1995.

Fig. 7.3. Map of deltas which are heavily populated and vulnerable to sea level rise

Source: Nicholls & Leatherman, 1995a.

Box 7.3. The Nile Delta

Although the Nile Delta is not greatly affected by storms, it does typify the intense and growing pressures that many deltas are currently experiencing, irrespective of future sea level rise. The Aswan Dam was built on the River Nile in 1964. Accordingly, no sediment and very little fresh water enters the Mediterranean from this river. The Rosetta and Damietta headlands are therefore eroding, although part of their shorelines continue to accrete.

The Mediterranean coast of the delta is lined with sand dunes that are 1–5 m in height, behind which is found a series of large shallow brackish lakes that supply approximately 50% of the nation's fish catch. Dunes require replenishment from wind-blown beach sands, and it is likely that this dune system will degrade if current erosion levels continue and sea level rise also occurs. Rates of local subsidence will probably increase owing to unsustainable use of surface and groundwater sources.

In common with many delta areas, a growing population and poor resource management have combined to increase the risks presented by climate change and sea level rise. Recent estimates, based on a scenario of a 1 m rise in sea level, project a loss of up to 15% of habitable land. Over 3.2 million people and 70% of Egypt's industry are situated at Alexandria, large parts of which can be expected to experience negative impacts from sea level rise. In total, a population of around 6 million (approximately 10% of the country's total population) could be displaced by a 1 m rise in sea level, if coastal protection is not established.

Sources: El-Raey, 1990; El-Raey et al., 1995; Strzepek et al., 1995.

most of which is highly productive agricultural land — and displace around 750 000 people (Asthana et al., 1994). In the Niger delta in Nigeria, a 1 m rise in sea level by 2100 could inundate about 15 000 km^2 of land; since conventional protection does not appear to be feasible, around half a million people could be forced to relocate (French, Awoskia & Ibe, 1995).

Potential health effects of sea level rise

Sea level rise caused by human-induced climate change would have a range of effects on human health (see Table 7.2). But these are likely to vary according to local circumstances, particularly geographic location, and the capacity of the community affected to respond to sea level rise and to extreme weather events. Additionally, the potential effects of sea level rise on health cannot be considered in isolation from the impacts of other stresses such as storm surges. Table 7.3 lists some of the factors that determine population vulnerability to sea level rise.

Quantifying the potential effects of sea level rise on health is also difficult because impacts may be cumulative, and may interact synergistically. For instance, destruction of agricultural land and reduced fish catches would affect local nutrition levels adversely and could also trigger local economic decline, which could in turn reduce the resources available for health care, and for maintenance of infrastructure such as water supply systems, telephone lines, hospitals and roads. Studies, particularly historical analogue studies, that would allow definitive statements to be made about the potential effects of sea level rise on human health, are lacking however.

Extreme weather events and coastal flooding

Coastal zones are often affected adversely by temperature and precipitation extremes, cyclones and storm surges (Bijlsma et al., 1996). Many climate models suggest that in a warmer climate the probability of heavy rainfall events will increase. However, global climate modelling is still at a relatively early stage and prediction of long-term changes in the frequency and/or intensity of extreme events at a local level is not possible (see Chapter 2). Another area of uncertainty concerns how changes in climate variability would interact locally with sea level rise and affect coastal zones. Evidently though, it can be anticipated that in low-lying coastal zones, more intense rainfall events, combined with sea level rise, would increase the likelihood of flooding (Nicholls, Mimura & Topping, 1995). This in turn would result in injury, death, displacement, and increased risk of various (especially water-related) infectious diseases. Any increase in tropical cyclones, hurricanes or typhoons, and the floods that accompany them, could also have serious health impacts (see Chapter 6).

However, even if the frequency of extreme weather events changes little, sea level rise would itself be sufficient to increase the risk of coastal flooding, simply because baseline sea level would become higher. Indirect effects of sea level rise could include loss of protective natural features such as dunes and mangroves, due to increased erosion and reduced drainage of coastal streams as a result of increased backwater effects. Increased erosion and reduced drainage would also increase the risk of flooding. Quantitative estimates, in relation to specified rises in sea level, of the number of people who would be at risk of flooding, have been made. These estimates, some of which are given above, are based on the current frequency of storm surges, current population estimates and highly simplified assumptions of levels of protection (if these are considered at all). However, the human impact of flooding will also depend upon factors such as the extent and efficiency of the public health infrastructure, societal trends and levels of disaster preparedness. Accurate quantification of these factors has not yet proved possible.

In the meantime, therefore, preventive action should be planned, such as how to ensure effective flood warnings. Flood warnings can reduce mortality rates significantly, particularly if a population has previous disaster experience and is accordingly more able and more inclined to take preventive action. The health impacts of floods can also be reduced by designing a multiple water-supply system so that damage to one system or one part of the system does not jeopardize a population's water supplies completely. Similarly, continued transport of water supplies to remote areas during a disaster is more likely to be guaranteed if a number of delivery routes are created. Natural coastal defences such as wetlands should also be protected since these buffer storms.

Table 7.2. Potential effects on health of sea level rise

- Death and injury due to flooding (as a result of greater susceptibility to extreme events).
- Effects on nutrition of loss of agricultural land or changes in fish catch.
- Reduced availability of fresh water due to saltwater intrusion.
- Contamination of water supplies, via disruption of sanitation, e.g. by microorganisms such as *Vibrio cholerae,* or pollutants from submerged waste dumps.
- Changes in distribution of disease vectors (e.g. *Anopheles sundaicus*, a saltwater vector of malaria).
- Effects of local economic decline on mental and physical health.
- Health impacts associated with population displacement.

Freshwater quantity and quality

The most immediate and significant short-term effect of sea level rise on freshwater supply and quality would be due to flooding. (The health effects of reduced availability of fresh water are discussed in detail in Chapter 4.) However, the more long-term effects of sea level rise on groundwater resources are uncertain, although it is known that saltwater intrusion of aquifers could become a major problem in coastal cities such as Dakar in Senegal and Shanghai in China, owing to local geography and hydrology (Dennis, Niang-Diop & Nicholls, 1995; Wang et al., 1995). On small islands, groundwater systems, typically confined to freshwater "lenses", and difficult to protect, would also be very susceptible to saltwater intrusion. Unfortunately, restoring freshwater aquifers that have been damaged in this way is extremely difficult. Saltwater intrusion has been observed already in Israel, north China and southern USA, and on the Marshall Islands in the Pacific. On the Marshall Islands, non-sustainable use of local water resources and high population growth rates have been contributory factors. Water intended for domestic use can be desalinated if saltwater intrusion is only minor, but it is a very expensive process. The implications of sea level rise for freshwater supply should be investigated more widely, including the potential for adaptive responses.

In low-lying coastal areas, a rise in sea level could also raise the water-table, leading to release of contaminants — for example, viruses and bacteria from septic systems — into waterways. This would pose either a direct hazard to the local population, or an indirect hazard if contaminants entered the food chain.

Vector-borne diseases

Changes in the transmission of infectious diseases as a result of sea level rise are likely to be complex. The effect of sea level rise on vector-borne diseases, particularly malaria, will depend partially on local factors such as coastal geomorphology and the natural history of the local vector species (Molineaux, 1988). For example, in Africa generally, the main vectors of falciparum malaria are members of the *Anopheles gambiae* complex, but any increases in the availability of brackish water would tend to result in replacement of the very efficient vectors *An. gambiae* and *An. arabiensis* by the less efficient *An. melas* and *An. merus*. The latter two species tolerate salt water in West Africa and East Africa, respectively. Thus a rise in sea level is likely to lead to reduced malaria transmission in some coastal zones, although whether this would be reflected by reduced incidence of clinical malaria attack rates is unclear.

Elsewhere, sea level rise is likely to result in higher incidence of malaria. In south and south-Asia, the larvae of several malaria vector species, including *An. sundaicus*, which is a vector in Indonesia, Malaysia, Myanmar and southern Bangladesh, are salt-tolerant. Mud flats in these countries are densely populated, so if sea level rise leads to greater intrusion of salt water, vector populations might multiply, making malaria an even greater health risk for local populations. However, other populations of *An. sundaicus* in Indonesia are freshwater breeders and can be reduced by allowing salinity to rise (Takken et al., 1991).

An. aquasalis is also salt-tolerant and a potential malaria vector, under specific environmental conditions, in northern parts of South America. Predicting the impacts of sea level rise on malaria transmission by this particular species, however, would require detailed studies of relevant local ecological conditions, including the population dynamics of its animal hosts.

Table 7.3. Factors that influence the impact of sea level rise on human health

Climate	Changes in the frequency of extreme events (storms, cyclones, etc.)
	Changes in patterns of local precipitation
Physical	Integrity of local ecosystems (e.g. mangroves, coral reefs, etc.)
	Local subsidence
Socioeconomic	Economic development and resources for mitigation
	Population growth and density
	Provision of storm protection and warnings
	Flood control programmes
	Provision of clean water
	Health care infrastructure
	Community organization
	Family support

Food availability

Globally, approximately 70% of commercial fish species are estimated to depend on coastal near-shore or estuarine habitats at some point in their life cycle (Everett et al., 1996). Wetlands and coral reefs, for instance, serve as nurseries for many fish and shellfish species. Sea level rise could impinge on local food production through its impacts on such ecosystems. It will also affect food production, if, as anticipated, it leads to destruction of agricultural land, increased flooding and saltwater intrusion of agricultural water supplies. Small island nations could be affected particularly adversely since they find the cost of importing food to be high relative to their population size (Reilly et al., 1996).

The possibility of declines in rice production is also of concern. Around 8% of the world's rice is produced in south-east Asia in areas that are likely to undergo some of the most serious impacts of sea level rise. These areas produce rice that feeds around 200 million people. Around 75 million of them could be deprived of their main food source if sea levels were to rise half a metre by the year 2100 (Hoozemans et al., 1993). Populations in the large deltas in south and south-east Asia would be affected most severely.

Population displacement

Various populations could be displaced by sea level rise (Myers & Kent, 1995). These would include populations living on land with a high risk of flooding, in poor circumstances, whether in rural or urban settings. For example, in Indonesia, many of the people at greatest risk live in economically and socially impoverished transmigration settlements in coastal zones, which are commonly situated on poor agricultural land. Many shanty settlements in developing countries could also be affected. Such settlements have often sprung up heedless of planning guidelines, and their populations are growing rapidly. There are many of these settlements in large coastal cities such as Bangkok, Bombay, Calcutta, Karachi, Manila, Lagos, Jakarta, Lima and Rio de Janeiro (Devine, 1992). The effects on human health of displacement will depend upon the rate of displacement, but this is very difficult to assess (see also Chapter 6). Population displacement or movement could be triggered by a reduction in food sources and availability, loss of land, storm damage, and economic decline following negative impacts on economic activities such as fishing, tourism, recreation and transportation.

Response strategies

Coastal nations should implement comprehensive coastal zone management plans to minimize the impacts of sea level rise (see also Chapter 10, Box 10.2) (IPCC, 1990b; 1992; WCC'93, 1994). Developed nations can assist developing nations to do this by providing technical aid. The plans should ensure that the risk to human populations is minimized, that important ecosystems are maintained and protected, and that development in coastal zones is sustainable. Additionally, national efforts should be made to identify particular services and resources at risk, and to formulate response strategies. The implications, such as cost, and the health impacts of adaptive response measures, should also be assessed.

Response strategies fall into three broad categories:

- Retreat: abandonment of vulnerable areas and resettlement of their former inhabitants.
- Adaptation: continued occupancy and use of vulnerable areas after modification of land and resource use.
- Protection: defence of vulnerable areas, with particular attention paid to population centres, economic activities and natural resources.

Retreat may be planned or unplanned. In many situations planned retreat will be the least expensive response to sea level rise.

Assessments of the costs of adaptation and protection have been made (Bijlsma et al., 1996). Table 7.1 illustrates the considerable variation between countries in these potential costs, as a percentage of GNP: from 0.02% for North America and north and west Europe, to 0.1% for countries along the South American Pacific coast, to 0.77% for small islands in the Pacific. For this last group, the cost per capita is more than US$ 1800. However, GVA cost estimates may underestimate total costs, since they do not take the costs of retreat measures, water resource management and management of infrastructure into account (Nicholls, 1995b). Moreover, although a wide range of possible response options exists at the local level, most analyses have considered only the two extremes of unplanned retreat or total protection (Bijlsma et al., 1996). Yet at the local level, it is likely that a range of responses would be adopted (Turner, Adger & Doktor, 1995; Volonté & Nicholls, 1995).

Increasingly, proactive adaptive measures are being investigated and applied (Nicholls & Leatherman, 1995b; Bijlsma et al., 1996). For instance, in Massachusetts, USA, the height of a sewage plant was increased by 0.46 m so that in the event of higher sea levels, gravity-based flows can be maintained without additional pumping (Smith & Mueller-Vollmer, 1993). Fankhauser (1995) has concluded that implementing such protective measures against a 50 cm rise in sea level by 2100 would prove cost-effective for OECD countries. This would not be the case for many developing countries, however, since their coastal defences are less well established. However, the dominant economic activity in their coastal zones is often fishing or agriculture which means that coastal assets represent a large proportion of overall wealth and that any losses incurred would constitute a greater proportion of GNP. Flexibility is therefore called for when devising measures to prevent or mitigate the impacts of sea level rise. This will help ensure that developed and developing countries alike are able to implement measures that are adequate to their needs and within their financial means.

Chapter 8

Stratospheric ozone depletion

Stratospheric ozone depletion and greenhouse gas accumulation

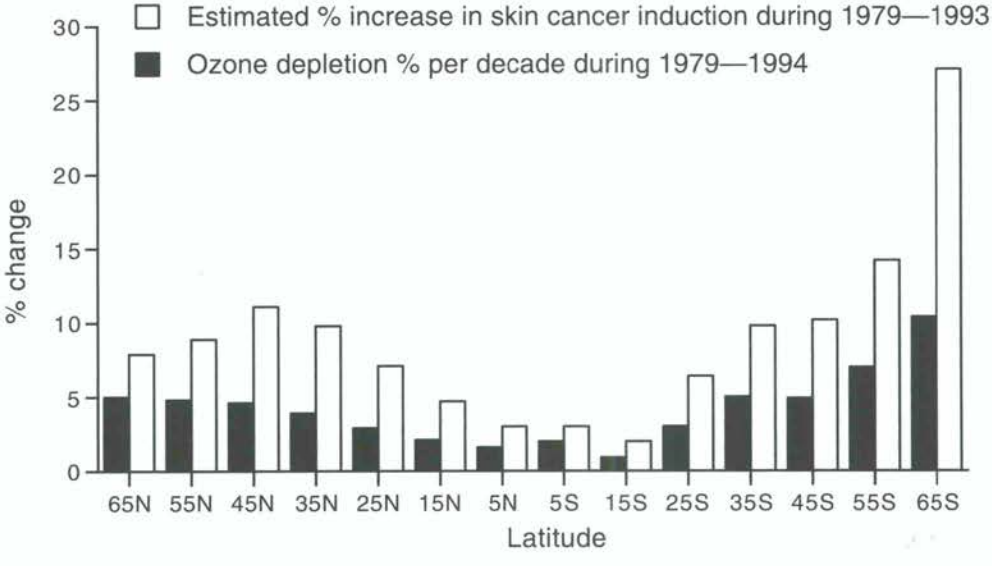
Climate and weather are often thought of as products of the *lower* atmosphere (i.e. the troposphere). The inclusion of a chapter about the depletion of ozone in the stratosphere (i.e. the *middle* atmosphere) may therefore seem inappropriate. But climate change and stratospheric ozone depletion are linked by virtue of various chemical and physical relationships, and these provide sufficient reason for considering stratospheric ozone depletion when making an overall assessment of the health effects of climate change (see also Chapter 2; see also Rind & Lacis, 1993 and WMO et al., 1994). Nevertheless, the essential difference between greenhouse gas accumulation and stratospheric ozone depletion should be borne in mind. Greenhouse gas accumulation increases the effect of radiative forcing on climate, while destruction of stratospheric ozone by chlorine radicals leads to increased ultraviolet radiation (UVR) at ground level. These two distinct phenomena are thus members of a wider-ranging family of global environmental changes now emerging in our "overloaded" world (McMichael, 1993).

Increases in ground-level ultraviolet radiation

Stratospheric ozone (O_3) accounts for about 90% of all atmospheric ozone. Found mostly at an altitude of between 15 km and 25 km, at concentrations below 10 ppmv, it absorbs significant quantities of incoming solar radiation, thereby affording protection from UVR at Earth's surface (WHO, 1994c). Of the solar radiation that reaches Earth's surface, approximately 5% is ultraviolet, a further 55% is infrared and 40% is visible. The UV wavelength band spans 200–400 nm and is conventionally subdivided into UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm). Stratospheric ozone absorbs essentially all of the highest-energy, shortest wavelength radiation (i.e. UV-C), approximately three-quarters of the next highest energy band (i.e. UV-B), but only a small part of the lowest energy radiation (i.e. UV-A). Further UVR is absorbed in the troposphere via clouds, dusts, and gaseous and particulate air pollutants. The total proportion of UVR absorbed in the atmosphere is a function of the time taken by incoming solar radiation to reach Earth's surface. Therefore, the intensity of UVR at ground level varies significantly with the angle of incoming solar radiation, and hence, with the time of day, season, and latitude. Clear-sky UVR reaches its highest levels at low latitudes. Conversely, its levels are lowest at the north and south poles.

Stratospheric ozone depletion first became evident in the 1970s. By the mid-1980s and early 1990s, at northern mid-latitudes of 30–60°N (including most of the USA, northern Africa, much of continental Europe and much of Asiatic Russia) ozone depletion was occurring at the rate of around 0.4% per year (Kerr, 1992; Stolarski et al., 1992). Over approximately a decade this has led to ozone depletion of 6% during winter and spring, and 3% during summer and autumn.

Fig. 8.1. Estimated relationship between increases in stratospheric ozone depletion and skin cancer induction by latitude



Sources: UNEP, 1994a; data from Ozone Secretariat.

Meanwhile, in the southern hemisphere, cumulative ozone depletion has amounted to 5% per decade since 1980 (Armstrong, 1994; UNEP, 1994a). This depletion has occurred predominantly within the latitude band that extends from the south pole to 30°S (i.e. including the lower third of Australia and South America). Ozone depletion has increased during the 1990s and ozone depletion trends are now well-established in both hemispheres (Gleason et al, 1993; Jones & Shanklin, 1995).

Human-induced depletion of stratospheric ozone is much greater at high latitudes. Therefore, increases in ground-level UVR are anticipated to be greatest in the southern parts of Africa, Australia and South America, and at mid-latitudes (30–60°N) in Europe, Asia and North America (Madronich, 1992). Estimates from satellite measurements of ozone made during 1979–1992 indicate that UVR reaching the lower atmosphere has increased by approximately 3% per decade at 30°N (for example, in New Orleans, Delhi and Shanghai) and at 30°S (for example, in Sydney, Buenos Aires and Durban) (Madronich & de Gruijl, 1993).

Direct evidence of increased ground-level UVR is fragmentary and, until recently, did not agree with modelled estimates. This discordance is thought to have been attributable to a combination of spectrally non-specific measurements for some locations, calibration shifts that have occurred over time in some instruments, such as the widely-used Robertson-Berger meter, and variations over time in "interference" from industrial air pollutants that absorb or scatter incoming UVR, as has occurred, for instance, over parts of Germany (see Seckmeyer & McKenzie, 1992). Nevertheless, measurements of ground-level UVR made in some non-urban locations in New Zealand and the European Alps have agreed with modelled estimates, and coherent evidence of increases in ground-level UVR is growing (Blumthaler & Ambach, 1990; Zheng & Basher, 1993; WMO/UNEP/NOAA/NASA, 1994; Madronich et al., 1995). The percentage increase in UVR reaching the lower atmosphere is now thought to vary as an exponential rather than linear function of the percentage decrease in stratospheric ozone (Booth & Madronich, 1994). Any percentage increase in UV exposure would therefore exceed the increase predicted by a linear function, and this divergence would increase with increasing ozone depletion.

If the Montreal Protocol and its amendments (see Box 2.4) are complied with fully, stratospheric chlorine concentration, and hence ozone damage, should peak within the next decade or so. Maximum ozone losses, relative to the ozone levels of the late-1960s, are likely to be 12–13% at northern mid-latitudes in winter and spring, about 6–7% at northern mid-latitudes in summer and autumn, and about 11% at southern mid-latitudes. It is estimated that such changes would be accompanied by 15%, 8% and 13% increases, respectively, in ground-level erythemal UVR, if other factors such as clouds remain constant (WMO/UNEP/NOAA/NASA et al., 1994). These peak levels would then be expected to persist, and to decline only marginally for several decades thereafter, reflecting the long half-life of chlorine radicals in the stratosphere (Armstrong, 1994). Subsequently, recovery of stratospheric ozone would occur by replenishment, to the extent that 1990 levels would be regained by the middle of the next century (UNEP, 1994a).

Direct health effects of increased ultraviolet levels

Direct UV exposure has both harmful and beneficial effects on humans (see Table 8.1). For instance, humans require a small amount of UVR, especially UV-B, to synthesize vitamin D (Webb, 1993). Vitamin D is essential for maintaining stable blood calcium levels and, therefore, for the growth and maintenance of a healthy skeleton. However, UV exposure is generally harmful to both humans and many other biological organisms (de Gruijl & van der Leun, 1993). Sustained exposure to UV-B and UV-C is damaging, for example, to amphibian eggs, plants and marine phytoplankton (Teramura et al., 1991; Quaite, Sutherland & Sutherland, 1992; Holm-Hansen et al., 1993; Blaustein et al., 1994).

Both UV-B and UV-C are strongly absorbed by DNA (see Fig. 8.2). Under experimental conditions, UV-B has been shown to induce direct damage to DNA in proportion to the dose (Freeman et al., 1989; UNEP, 1994a). Additionally, longer wavelength UV-A "excites" light-sensitive molecules which then generate destructive free radicals that can damage large molecules such as DNA, and the crystalline protein in the lens of the eye (Tyrrell, 1994). DNA damage caused by free radicals may induce skin cancer, although much less potently than either UV-B or UV-C (de Gruijl et al., 1993). This molecular biological evidence, together with much epidemiological evidence, implicates UVR in the causation of skin cancer and eye lesions.

Although laboratory experiments have shown that UV-B is many thousand times more potent than UV-A as a cause of skin cancer in experimental animals, and as a cause of erythema, the longer wavelength UV-A penetrates human skin more deeply, reaching the subepithelial fibrous tissue. UV-A may therefore be more closely linked to skin damage and aging. However, although UV-B may be less damaging to the skin than UV-A, it has, in addition, damaging effects on the eye and on the body's immune system. The extent of the latter effect and the biological mechanism involved have not yet been established, but as the ozone layer becomes more depleted, the ratio of UV-B to UV-A that reaches ground level will increase, with the result that the various biological effects related to UV-B will predominate (Jeevan & Kripke, 1993; Longstreth et al., 1995).

Table 8.1. Summary of the main effects of solar ultraviolet radiation on the health of human beings

Nature of effect	Direction of effect	Strength of evidence
Effect on immunity and infection		
Suppression of cell mediated immunity	Harmful (?)	Sufficient
Increased susceptibility to infection	Harmful	Inadequate
Impairment of prophylactic immunization	Harmful	Inadequate
Activation of latent virus infections	Harmful	Inadequate
Effects on the eye		
Acute photokeratitis and photoconjunctivitis	Harmful	Sufficient
Climatic droplet keratopathy	Harmful	Limited
Pterygium	Harmful	Limited
Cancer of the conjunctiva	Harmful	Inadequate
Lens opacity (cataract)	Harmful	Limited
Uveal melanoma	Harmful	Limited
Acute solar retinopathy	Harmful	Sufficient (?)
Macular degeneration	Harmful	Inadequate
Effects on the skin		
Malignant melanoma	Harmful	Sufficient
Non-melanotic skin cancer	Harmful	Sufficient
Sunburn	Harmful	Sufficient
Chronic sun damage	Harmful	Variable
Photodermatoses	Harmful	Sufficient
Other direct effects		
Vitamin D production	Beneficial	Sufficient
Other cancers	Beneficial	Inadequate
General well-being	Beneficial	Inadequate
Indirect effects		
Effects on climate, food supply, disease vectors, air pollution, etc.	Probably harmful	Inadequate

Limited = suggestive but not conclusive evidence; ? = some uncertainty about assigned classification
Source: Armstrong, 1994.

Skin cancer

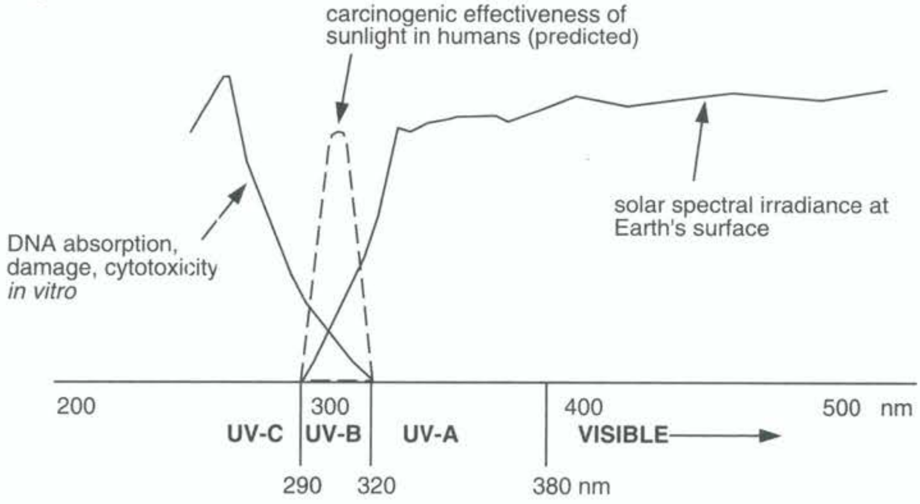
Many epidemiological studies have implicated solar radiation as a cause of skin cancer (both melanotic and non-melanotic) in fair-skinned humans (IARC, 1992; WHO 1994c). In recent years, UV-specific mutations of prominent cancer-associated genes, such as *ras*, the p53 gene and the MTS-1 melanoma-associated gene, have been identified in several types of skin cancer, but particularly in skin cancer occurring in UV-sensitive patients with the DNA repair-deficient disease xeroderma pigmentosum (IARC, 1992; Dumaz et al., 1993; Sage, 1993; Ziegler et al., 1993; Dumaz et al., 1994). While such mutations may directly cause malignant change in the cell affected, other forms of UV-induced DNA damage occur indirectly via modification of cellular activities, including those that contribute to the body's immune system (Chapman et al., 1995).

Non-melanotic skin cancers (NMSCs) are of two major histological types: basal cell carcinoma (BCC) and squamous cell carcinoma (SCC). The ratio of BCC to SCC in fair-skinned populations is 4:1. Most NMSCs occur on exposed sites, especially the head and neck, and incidence rates tend to be higher in men. The risk of these cancers has generally been thought to correlate with cumulative lifetime exposure to solar radiation. But recent evidence suggests that the relationship is more complex — at least for BCC, for which it appears that childhood exposure may be important (Vitasa et al., 1990; Kricker et al., 1995).

Malignant melanomas are produced by the pigment-producing cells of the skin (melanocytes). Their relationship with solar radiation, however, is not simple. Many melanomas occur on the less irradiated (especially trunk) sites of the body, suggesting that mechanisms — mediated by hormonal or immunological factors and that are not damaging to DNA — may be involved. Solar exposure in childhood is a major factor; exposure patterns, as well as the amount of exposure, influence the risk. For cutaneous melanoma it is not clear which UV waveband contributes the most to causation. A tropical fish model suggests that UV-A as well as UV-B may be implicated (Setlow, Woodhead & Grist, 1989). But although animal models are instructive because they demonstrate that UVR can contribute to the induction of melanotic tumours, they are not appropriate for assessing dose–response relationships in humans.

Overall, 60–90% of melanomas in fair-skinned populations are estimated to involve sunlight exposure (Armstrong & Kricker, 1993). The incidence of melanoma in white populations has risen by 3–7% every year since at least the 1960s, and probably reflects a progressive increase in average levels of personal exposure to solar radiation, due to changes in patterns of recreation, clothing and occupation that are unrelated to stratospheric ozone depletion (Armstrong & Kricker, 1994). Increases in melanoma incidence in western populations have occurred in all age-groups, although some recent evidence indicates a downturn — probably related to behaviour — among younger people (Armstrong & Kricker, 1994).

Fig. 8.2. Diagrammatic representation of the range of ultraviolet and visible radiation, the relative incidence of different wavelengths at Earth's surface, and the predicted source of cancer risk (carcinogenic effeciveness) as the product of both incident radiation and the experimentally-shown "action spectrum" for DNA damage



Source: Tyrrell, 1994. Reprinted with kind permission from Elsevier Science Ltd.

How might further depletion of stratospheric ozone affect skin cancer rates around the world? According to UNEP (1994a), an average global depletion rate of 10%, as emerged at mid to high latitudes between 1979 and 1992, if sustained globally for the next 30–40 years, would result in approximately 250 000 additional cases of NMSC worldwide each year. Calculations assume that behavioural and demographic risk factors do not change, and that current ozone depletion rates and UV exposure increases are sustained during the next several decades. (Cancer often has a latency period of 30–40 years). UNEP (1991) had previously also predicted an extra 4500 cases of malignant melanoma under such circumstances, but the estimates for this type of skin cancer are now regarded as less certain.

The above prediction relating to future NMSC incidence assumes that stratospheric ozone depletion of 1% results in a 2.0% (±0.5%) increase in NMSC incidence. Other research has indicated that the increase in NMSC incidence would be closer to 2.25% (Slaper et al., 1992; den Elzen, 1994). Using a higher geographical resolution, Madronich & de Gruijl (1993) have predicted that, if ozone depletion levels were to remain at levels incurred during 1979–1992 for the next several decades, BCC incidence would increase by 1–2% at a low latitude of 5°, by 3–5% at latitudes between 15° and 25°, and by 8–12% at latitudes between 35° and 45° and between 55° and 65°, and by 13–15% in the northern hemisphere and 20–30% in the southern hemisphere. They estimate that the percentage increases for the less common squamous cell carcinoma would be approximately double those for BCC.

Predictions of changes in cancer risk due to ozone depletion must allow for cancer latency. The gradual cumulation of the extra risk (over time) must also be considered. The failure of some earlier published predictions to take such considerations fully into account may have resulted in overestimates of the numbers of extra cancers (Kricker, Armstrong & McMichael, 1994).

Cataracts and other damage to the eye

The external epithelial layer of the eye, consisting of the cornea and conjunctiva, absorbs virtually all UVR with a wavelength of less than 290 nm (i.e. UV-C). Damage to the eye's outer tissue that is thought to be related to UV exposure includes corneal photokeratitis ("snow blindness"), pterygium, and possibly climatic droplet keratopathy. Photokeratitis is associated with acute exposure, and pterygium and climatic droplet keratopathy with chronic exposure (Taylor, 1989; Gray et al., 1992; WHO, 1994c, 1994d).

Normally, the aqueous humour, lens and vitreous humour of the eye do not absorb visible light but do absorb any residual UVR that penetrates the cornea. UV exposure in the 300–380 nm wavelength (UV-A) that occurs within the eye is thought to cause cataracts of the lens (Taylor et al., 1988; Dahlback et al., 1989; Dolin, 1994; WHO, 1994c, 1994d). Since UV-A has a substantial capacity to generate free radicals in ocular tissue, and therefore to damage protein molecules, and has a greater penetrative capacity than UV-B, it is plausible that UV-A can cause significant damage to the eye. However, little evidence with respect to either humans or experimental animals has been found to support this assumption (Tyrrell, 1994). Higher wavelength UVR (i.e. UV-A) that reaches the retina may cause macular degeneration (West et al., 1989; Young, 1989).

Unlike skin cancer, cataracts are not related to skin pigmentation. They occur mostly in old age and account for over half of the world's estimated 25–35 million cases of blindness (Harding, 1991; Thylefors et al., 1995). In western countries, 5–10% of people over the age of 65 have cataracts; in poor countries, prevalence is often much higher, since micronutrient deficiencies and severe diarrhoeal episodes — which are believed to contribute to cataract formation — are common (Harding, 1992; Klein et al., 1992). UNEP (1994a) has suggested that, uncertainties aside, the best current estimate is that for each 1% depletion in stratospheric ozone, cataract incidence would increase by 0.6–0.8%.

Meanwhile, scientific debate persists over the role of UV-B in cataract formation (Dolin, 1994; WHO 1994d). Some epidemiological studies have found positive relationships, others have not (see, for example, Taylor et al., 1988). The positive findings have been predominantly for cortical and posterior subcapsular cataracts, rather than for the more common nuclear or centrally-located cataracts. Thus a recent study that re-analysed data from a large study in Italy, reported positive dose–response relationships between cumulative personal UV exposure and the incidence of cortical and posterior subcapsular cataracts, both in isolation, and in conjunction with nuclear cataracts, but not for nuclear cataracts in isolation (Rosmini et al., 1994). A plausible explanation as to why UV-B affects mainly the periphery or posterior layer of the lens can be given; that is, biological theory and *in vitro* studies indicate that UV-B can produce reactive photo-oxidation by-products in the lens, causing cross-linking and distortion of large protein molecules, leading to increased scattering and absorption of light (UNEP, 1994a). However, more precise quantitative epidemiological data pertaining to the relationship between UV-B exposure and risk of cataract are needed.

Attention should also be paid to the fact that certain drugs used in photochemical therapy can cause photosensitizing reactions and may therefore exacerbate ocular damage resulting from UV exposure (Lerman, 1988). Accordingly, they could render individuals more susceptible to any adverse health effects arising from increased UV exposure. These drugs include retinoic acid compounds (used to treat acne) and psoralens, thiazides, phenothiazines, barbiturates and allopurinol (Lerman, 1986).

Alteration of immune functioning

The human immune system is very complex. In essence, it comprises a repertoire of responses designed to detect and protect the body from "foreign" antigenic material, particularly that of infectious disease agents. Its responses encompass local (e.g. skin) responses and systemic (i.e. pertaining to the whole body) responses, and entail cell-mediated and humoral processes. The immune system's various components often act complementarily, which requires coordination and balance. Hence, a change in one component can affect other components, causing simultaneous enhancement or suppression of different elements of the immune response. Much remains to be discovered, though, about the relative importance of and the compensatory mechanisms operating between these various components.

Human and animal studies indicate that UV-B irradiation of skin at quite low levels causes local and probably some systemic immunosuppression (Morison, 1989; Kripke, 1990; Noonan & DeFabo, 1992; Jeevan & Kripke, 1993). But the extent and significance of this with respect to disease incidence in humans are still uncertain. Nor is much information yet available about the effects on immune function of sustained or repeated UV exposures (Chapman et al., 1995). There are several indications, though, that ambient UV exposure levels do affect immune functioning.

Indeed, the shape of the "action spectrum" for one form of UV-induced immunosuppression suggests that ground-level solar radiation is more closely associated with immunosuppression than with either sunburn or damage to DNA.

Evidence has also been collected to the effect that in humans and experimental animals, UVR causes local immunosuppression in the skin, resulting in impairment of both contact and delayed-type hypersensitivity (Giannini, 1986; Yoshikawa et al., 1990; UNEP, 1994a; Chapman et al., 1995). The ability of UV-B to impair both delayed-type and contact hypersensitivity responses is significant since these forms of cell-mediated immunity are important in relation to some infectious diseases and the immune response to cancers (Chapman et al., 1995). Other evidence indicates that UV exposure impairs the function of the skin's Langerhans (antigen-presenting) cells and stimulates the release of certain cytokines (messenger chemicals), thereby redirecting the immune response toward suppressor T-lymphocyte formation, and thus dampening local immunity (Scheibner et al., 1987; Alcalay, Craig & Kripke, 1989; Simon et al., 1991; UNEP, 1994a). Moreover, although the mechanisms of local immunosuppression remain uncertain, UVR clearly upsets the balance of chemical factors and cell types involved in the induction of contact hypersensitivity responses.

It appears that UVR effects on systemic immunosuppression relate especially to cell-mediated immunity (Goettsch et al, 1993; Kripke, 1994). Evidence for systemic immunosuppression came first from studies with experimental animals. UV-irradiated mice show a reduced capacity to reject transplanted skin tumours (Kripke, 1981), to respond to *Mycobacterium bovis* BCG, and to respond to antigenic challenge at sites remote from the UV-irradiated site (Jeevan & Kripke, 1990 Noonan & DeFabo, 1990). In mice, UV-B irradiation enhances the growth of melanomas (Donawho & Kripke, 1991a; 1991b). In humans, exposure to UV-B-enriched radiation in solariums has been observed to increase the number of circulating suppressor (CD8) T-lymphocytes, while reducing the number of helper (CD4) T-lymphocytes (Hersey et al., 1983; Chapman et al., 1995). This change in the profile of circulating T-lymphocytes lasts from several days to weeks and therefore appears to be temporary (Chapman et al., 1995).

The mechanism by which UV irradiation of the skin affects circulating lymphocytes has not yet been identified (Arlett et al., 1993). However, it is likely to involve soluble chemical mediators produced in the skin following UV exposure. For example, urocanic acid, a molecule present in large quantities in the epidermis, absorbs UVR to form a more soluble *cis*-isomer which is known to suppress immune reactions in mice. Thus urocanic acid may mediate some of the immunosuppressive effects of UV exposure. Other evidence indicates that UV-induced DNA damage may trigger the release of cytokines, which also reduce immune function (Tyrrell, 1994; Noonan & DeFabo, 1992). Several important human pathogens (such as *Schistosoma* and *Ankylostoma*) gain entry to the body via the skin, while some infective pathogens also reproduce in the skin, such as those associated with leprosy and some rickettsial diseases. Increases in UV exposure could potentially modify those infections which gain entry through the skin. However, the potential mechanisms relating to the effects of UVR on systemic immunosuppression involving pathogens at the skin surface have so far not been clarified. Some impairment is assumed, but remains speculative since research has not yet been carried out in this area.

Evidently, the nature and extent of systemic suppression of the immune system following UV exposure are far from being fully understood (de Gruijl & van der Leun, 1993). But it seems clear that UVR shifts the balance of cell-mediated immune responses from effective to suppressed immunity. This could have implications for the risks and severity of infectious diseases, the progression of cancers, and responsiveness to vaccination (Armstrong, 1994; Chapman et al., 1995).

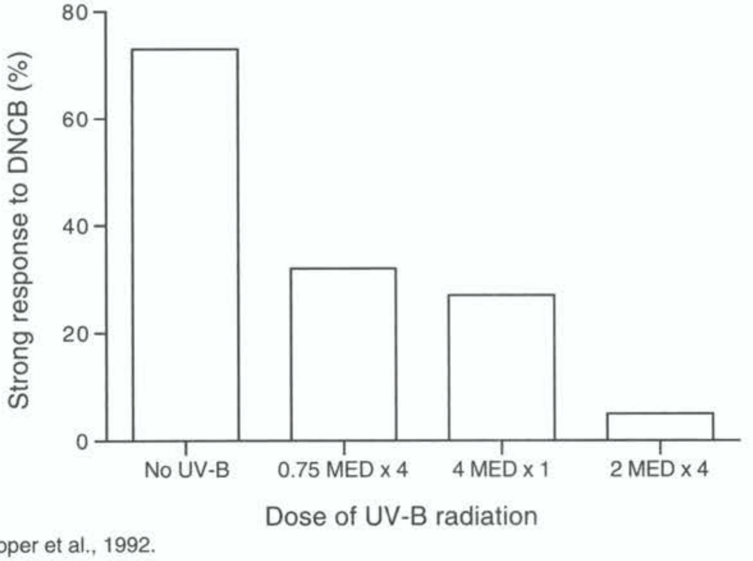
The balance between cell-mediated and humoral immune responses may be critical to the outcome of infectious processes (Scott & Kaufmann, 1991). Sudden changes in natural UV exposure can reactivate infection by *Herpes simplex* virus (cold sores) and by the human papilloma virus. They may also influence the clinical manifestation of leprosy lesions (Chapman et al., 1995). To assess the importance of this phenomenon to humans, extrapolation from results obtained from experiments with mice is needed. Studies in mice indicate that UV-B modifies various immunological reactions that may be significant to the pathogenesis of infectious diseases, such as those due to infection with *Herpes simplex* viruses, *Leishmania*, *Candida*, *Schistosoma* and mycobacteria (Giannini, 1986; Howie et al., 1986; Otani & Mori, 1987; Yasumoto, Hayashi & Aurelian, 1987; Denkins, Fidler & Kripke, 1989; Giannini & DeFabo, 1989; Jeevan & Kripke, 1989; Jeevan et al., 1992). The first two of these cause primary infections in the skin; therefore the local as well as systemic immunosuppressive effects of UV-B could alter the pathogenesis of the diseases caused by these organisms. Other evidence suggests that UVR may influence infectious disease outcome by suppressing humoral immune response (Chapman et al., 1995).

The Environmental Effects Panel of UNEP (1994a) recently concluded that: "There is now ample evidence that exposure of human and experimental animals to UV-B radiation from artificial or natural sources can modify the immune system both at the site of exposure as well as systemically, mainly by decreasing cellular immune responses". The relevance of these findings for naturally-occurring infectious diseases in humans is still not known, however. UNEP (1994a) has therefore concluded that assessment of the role of UV-B radiation on natural infections in human populations will be very difficult. UNEP considers that, given current knowledge, increased UV-B radiation levels can be anticipated to increase the severity or duration of disease, but not necessarily disease incidence.

Because of these unresolved questions, estimating the impact that increased UV-B exposure would have on infectious disease patterns is not yet possible (Chapman et al., 1995). That said, it should be noted that for some populations in poorer countries, the margin between health and infectious disease is very narrow, with the result that even a modest immunosuppressive effect might tip the host–parasite balance in favour of disease. In addition to the above-mentioned effects on long-established infectious diseases, enhanced progression of HIV/AIDS is also a possibility. Various autoimmune diseases, such as systemic lupus erythematosus, may likewise be exacerbated (WHO, 1992a).

Higher UV exposure could also reduce vaccination efficacy. So far, though, little direct evidence has been found testifying to such an effect. One experiment in young fair-skinned adults found that relatively small increases in low-level but UV-B-enriched UV exposure resulted in decreased local immune responsiveness to 2,4-dinitrochlorobenzene (DNCB) at the irradiated site (Cooper et al., 1992). The inhibition of local contact hypersensitivity immune response first appeared at 0.75 MED (minimal erythemal dose; 1 MED = 291 Jm^{-2} to 325 Jm^{-2}, depending on the individual); responsiveness became inhibited completely in nearly all subjects after they had received 2 MED daily for four days prior to antigen administration (see Fig. 8.3). In another experiment, and using a different methodology, Yoshikawa et al. (1990) failed to suppress contact hypersensitivity to

Fig. 8.3. Effect upon immune function of different configurations of increasing doses of ultraviolet radiation, given to the skin at the site of subsequent sensitization with dinitrochlorobenzene (DNCB). The outcome measure is delayed type hypersensitivity to DNCB (i.e. late response to challenge with DNCB) at a distant unirradiated site.



Source: Cooper et al., 1992.

DNCB in 50–60% of healthy individuals irradiated at higher UV doses for four days. They designated these subjects UV-B susceptible (UVB-S) and suggested that UV susceptibility is genetically controlled. The degree of immunosuppression correlated with the degree of Langerhans cell depletion within the skin. Immune response was also depressed in over a quarter of the subjects when re-challenged at non-irradiated skin sites, although the immunosuppressive effect did not extend to other unrelated antigens (Selgrade et al., 1995).

It has been suggested that both light-skinned and dark-skinned populations exhibit similar levels of immune suppression in response to UV exposure (Vermeer et al., 1991). However, other evidence suggests that a white-skinned person would experience an immunosuppressive effect at about half the UV dose at which a dark-skinned person would experience the same effect (Oberhelman et al., 1994).

Indirect health effects of increased ultraviolet levels

Terrestrial and aquatic surface-dwelling organisms are believed to have evolved only after the ultraviolet-shielding "layer" of stratospheric ozone had become sufficiently dense, around half a billion years ago — that is, within the most recent one-tenth of Earth's history. Life on Earth had previously been confined largely to the relative safety of aquatic environments, where it was shielded substantially from incoming UVR. Therefore, increased ground-level UV exposure at this point in time could affect terrestrial and aquatic organisms adversely, and disturb the balance of species within ecosystems. Many plant species, but also some animal species, especially those in which important life stages occur close to or not far below water surfaces, would be affected. This could ultimately reduce the productivity of food-producing ecosystems, both on land and in the oceans. Global food production would decline as a result, and hunger and malnutrition in human populations accordingly rise (see also Chapter 5).

Terrestrial species

Experimental and field studies show that UV-B exposure can disrupt photosynthesis in plants, thereby reducing their growth rate, and increasing their susceptibility to disease (Teramura & Sullivan, 1994; WHO, 1994c). If this were to happen on a large scale, agricultural crop productivity could decline (Borman, 1989). Other effects of UV-B exposure — although these are not necessarily "damage" responses — are mediated by altered activity of critical genes and metabolic pathways. They include decreased leaf expansion, stem elongation, altered flowering time and pattern, and changes in chemical composition (UNEP, 1994a). However, plants could also respond to increased UV exposure by accumulating UV-absorbing compounds in their outer layers, which would presumably protect sensitive areas from UVR damage.

The available data are still limited, and apply predominantly to agricultural species. Furthermore, most of the studies have been undertaken in laboratory or greenhouse rather than field conditions. This means that little is yet known about the net impact of increased UV-B exposure combined with, for example, increased concentrations of atmospheric carbon dioxide (CO_2) and higher background temperatures. Increased UV-B exposure could also significantly affect non-agricultural ecosystems such as forests and grasslands. Timing of flowering and pollination, competitive balance between species, decomposition, and nutrient cycles, could also all be affected (UNEP, 1994a). Nevertheless, it has been established that plant species and strains vary in their response to UVR. Experiments with several hundred species and crop strains have demonstrated that approximately two-thirds of them are UVR-sensitive (Worrest & Grant, 1989). Peas, beans, melons, cabbages and mustard appear to be among the most sensitive plant groups. UV exposure also adversely affects the growth of maize, rye and sunflower seedlings. Experimentally, the yields of some varieties of soybean, the world's fifth most important crop, decline by up to one-quarter when UV exposure is increased by 25%, although little impact is observable at lower exposures. Studies of soybean, wheat and rice crop growth, in which the increases in atmospheric CO_2 and UVR anticipated for around the year 2050 were simulated, indicate that the adverse effects of UVR exceed any "fertilizer" effects of increased CO_2 (Teramura, Sullivan & Ziska, 1990).

However, great uncertainty remains over the precise extent to which increased UVR could reduce agricultural yield and forest growth. The effects of UVR on plant yield, under field conditions, have been documented in only a few studies. A six-year study on soybeans demonstrated that the adverse effects of UVR are modified by the prevailing microclimate (Teramura, Sullivan & Ziska, 1990). Synergistic effects between UVR and other climatic stresses are also possible. In addition, increased ground-level UVR could serve to intensify the formation of photochemical oxidants from urban air pollutants, which are known to be damaging to crop production (Chameides et al., 1994). In the longer term, differential effects of UVR upon coexistent plant species could eventually cause major shifts in ecosystem structure, functioning and productivity (Gold & Caldwell, 1983; UNEP, 1994a).

Aquatic species

Phytoplankton are the largest single group of photosynthetic primary producers and found close to the surface of all aquatic ecosystems. As the grass of the oceans, they convert almost 100 billion tonnes of carbon to organic material annually. Particularly profuse in coastal waters, the time spent at or near the water's surface by phytoplankton populations — and by invertebrate zooplankton that feed upon phytoplankton — is critical to the food-gathering and breeding activities of larger aquatic species (Hader & Worrest, 1991). In short, phytoplankton form the base of aquatic food webs, which in turn supply approximately 20% of all animal protein consumed by humans; indeed, this percentage is significantly higher in many developing countries.

Hundreds of types of phytoplankton organism exist and these vary in their sensitivity to UVR. Since they live near the surface of water, they would generally lack defences against increased UVR. UV-B, for instance, bleaches the cellular pigments of many freshwater and marine phytoplankton species and also impairs plankton motility (Hader & Hader, 1989a, 1989b, 1990; Eggesdorfer & Hader, 1991; Hader & Worrest, 1991). Any increase in the amount of UV-B that penetrates several metres below the ocean's surface would also impair the capacity of these species to photosynthesize. (However, some algae species are able to produce a protective pigment against UVR (WHO, 1994c).) The sensitivity to UV exposure of phytoplankton and zooplankton also means that stratospheric ozone depletion could reduce the length of their annual near-surface season.

If increased UVR were to have significant adverse impacts on phytoplankton and zooplankton, shrimp and crab larvae populations, and ultimately fish stocks, would decline. However, estimates of the threat posed by stratospheric ozone depletion to marine organisms in the oceans' upper layers vary widely. In one study, the photosynthetic activity of phytoplankton populations in regions beneath the Antarctic ozone hole were observed to fall by 6–12% (Smith et al., 1992). But more recently, it was estimated that, over a full year, the average reduction in photosynthetic production in the Southern Ocean, in response to a September–November well-developed ozone hole would be less than 1% (Holm-Hansen et al., 1993). Furthermore, the differential thinning of ozone according to latitude may mean that algae in polar waters would exhibit more UV-related damage than would algae in equatorial zones.

UV-induced suppression of phytoplankton photosynthesis would also diminish, at least marginally, the oceans' uptake of atmospheric CO_2. The oceans are the largest reservoir of reactive carbon on Earth, and phytoplankton constitute the crucial biological pump that moves carbon from surface waters to deep waters. A 10% decrease in marine phytoplankton populations would result in a reduction in the oceans' annual carbon uptake of around 5 Gt — an amount equal to that contained in annual CO_2 emissions arising from fossil fuel combustion (UNEP, 1991).

Increased UV-B exposure might also impair amphibian and fish reproduction. Eggs and larvae are often UV-sensitive; it has been observed that the hatching rate of eggs of various frog and toad species is reduced by increased UV-B exposure (Blaustein et al, 1994). This type of impact could impinge upon the food productivity of aquatic ecosystems, and also result in depletion of populations of the predators of the insect vectors that spread certain vector-borne infectious diseases.

Mitigation of stratospheric ozone depletion and its health impacts

Concern about depletion of stratospheric ozone by chlorofluorocarbons (CFCs), has resulted in national and international restrictions on their production and use. The Montreal Protocol is the primary vehicle for changing national policy and practice pertaining to CFCs (see Box 2.4). Given the discrepancies between the needs and circumstances of developed and developing countries, a less stringent timetable for the phasing out of use of CFCs has been accorded to developing countries.

Since CFCs are the primary refrigerants used in air conditioners, much time and energy have been devoted to finding replacements for them. Some alternative refrigerants are still at a developmental stage; early assessment of potential health and environmental impacts associated with their manufacture, use and disposal should help minimize any future negative effects that they might have.

Chlorofluorocarbon-replacement chemicals

Hydrochlorofluorocarbons (HCFCs) and the hydrofluorocarbons (HFCs) are the most popular CFC-replacement chemicals. The presence of a hydrogen atom in the molecular structures of these chemicals makes them more vulnerable to degradation by hydroxyl radicals (OH) and hence reduces their tropospheric lifetime (Fisher et al., 1990; Nelson, Zahniser & Kolb, 1993). However, *any* substance that decomposes in the stratosphere, and that contains chlorine, bromine or iodine, will contribute to ozone destruction. Studies have shown that the ozone destruction potentials of HCFCs are not comparable to those of CFCs, while limited data suggest that those of HFCs are very low (WMO et al., 1994). HFCs are now being used in the air-conditioning systems of vehicles (Ravishankara et al., 1993; 1994).

Very little toxicity information is available for most of the CFC-replacement chemicals (Anders, 1991). While CFCs are chemically and biologically unreactive in the troposphere, the converse is true for HCFCs and HFCs (Blake & Merger, 1974; Niazi & Chiou, 1975; NCI, 1978). For example, the presence of a carbon–hydrogen bond permits HCFCs and the HFCs to be oxidized by the cytochrome P-450 enzyme system (Loizou & Anders, 1993). In particular, HCFC-123 (CF_3CHCL_2) should be treated with some caution as its molecular structure is similar to that of the anaesthetic halothane ($CF_3CHBrCl$). This is cardiotoxic and produces a rare, but serious, immunologically mediated hepatitis (Harris & Anders, 1991; Harris et al., 1991; Yin, Jones & Anders, 1993).

The safety of by-products of the chemical processes used to produce CFC-replacements should also be considered. Trifluroacetic acid (TFA), for example, formed during the "defraudation" of HCFCs and HFCs, is a potential long-term contaminant of the aqueous environment. It has been found in industrialized areas at concentrations of 0.01–0.05 ng/m^3. TFA concentrations are anticipated to increase by a factor of 40 by the year 2100. However, although further research is needed to determine the ecological hazards posed by such an increase, it is thought unlikely that TFA levels will become so high as to be toxic to phytoplankton and hence a threat to food production (UNEP, 1994a).

Clearly, a full assessment of the biological effects of candidate CFC-replacements and their by-products is needed before they can be accepted for widespread use.

Future research and monitoring

It is apparent that our knowledge about the ways in which an in increase in ground-level UV exposure would affect human health is uneven and incomplete. So although it is near-certain that skin cancer rates would increase in fair-skinned populations, we lack detailed and quantitatively precise information about the other direct effects of increased UV exposure on human biology — especially regarding the eyes and the immune system. We have even less understanding of the extent to which its effects on other living organisms could in turn adversely affect human health.

Existing epidemiological data sets on the dose–response relationships between UVR and its various known and suspected direct health impacts, should therefore be improved. Since most conventional estimates of behaviour-associated risk (obtained from intra-population studies) are based on levels of personal UV exposure that have been assessed via "proxy" variables (such as average daily hours during which the individual was exposed to the sun, and number of serious sunburns experienced during childhood), they cannot yield estimates for actual absolute levels of ambient UVR, or absolute personal exposure. Future research should thus focus more on the association between directly-measured individual UV exposure levels and health-related responses. But direct assessment of individual UV exposure levels is difficult to achieve in epidemiological studies and so considerable reliance may have to be put on laboratory observations of animal models and cultured cells and tissues.

Understanding of genetic factors and lifestyle-based conditioning of UV-B susceptibility and other aspects of immunosuppression must also be improved. Meanwhile, biologists and ecologists should continue to elucidate the ecosystem-associated impacts of increased UV exposure on plants, animals and biological communities in complex, real-world settings. This will necessitate increased ground-level monitoring of UV exposure and the identification of biological indicators for early UV exposure damage.

Monitoring should proceed at various levels and should include:

- systematic regional and global monitoring of changes in UVR at Earth's surface (in association with continued monitoring of stratospheric ozone);
- monitoring of early indications of changes in the incidence of health outcomes in humans, with particular attention paid to biomarker precursors for skin cancer and eye disorders;
- monitoring of changes in patterns of biomass production on land and at sea, and in impacts of increased UV exposure on specific plant and animal species.

Monitoring strategies and activities are considered further in Chapter 9.

Chapter 9

Research and monitoring

Research and monitoring: related tasks

The preceding chapters indicate the complexity of the climate change–human health relationship. Given such complexity, research into and monitoring of this relationship are difficult. This chapter focuses on these two activities, which must each take into account:

- the vast spatial scale associated with assessment of potential climate change impacts on large geographical areas and on physical and chemical processes that operate at regional and global levels;
- the many biological and physical systems-based processes on which human population health depends;
- the unavoidable uncertainty inherent to predictions of the impacts of a previously unknown phenomenon;
- a broad timeframe, since predicting the health effects of climate change involves consideration of health effects that may occur in the near future and those that may not be experienced until several decades have passed, either because they take some time to develop following exposure, or because the exposure levels at which they develop will not be experienced until some time in the future.

A distinction is often made between studies into the causation of disease (i.e. epidemiology) and the application of the results of those studies to public health surveillance activities (i.e. monitoring). Further, in traditional public health science, a distinction is made between *surveillance*, which is the ongoing observation of the occurrence and spread of a disease based on standardized reporting and recording methods and *monitoring*, that is, the performance and analysis of particular measurements aimed at detecting changes (i.e. new trends) in the environmental or health status of populations (Last, 1995).

Epidemiological research — which to date has constituted the principal means of investigating how natural climate variability affects human health — and the monitoring of populations for changes in health status, are interrelated. Moreover, in the context of climate change and health, epidemiological research and monitoring should be considered largely interdependent. This is because our capacity to predict health impacts will necessitate expansion of empirical knowledge of climate-related changes in health, and this can be reliably gained only through monitoring. Moreover, monitoring may provide early indicators of the nature of the health effects of climate change, useful for scientists and policy-makers alike. For example, if malaria incidence increased in a number of locations in which local temperature had also increased during the preceding decade, the assessment and predictive modelling of other mosquito-borne infectious diseases would obviously be called for.

Environmental epidemiology research

In more conventional research contexts environmental epidemiology involves comparing the health differences of groups of people who have experienced or are experiencing different exposures, by means of empirical observation. Thus the *actual* experience, be it current or recent, of some locally-defined population is investigated. By analysing that experience, the epidemiologist can infer (i.e. deduce) the nature of the relationship between a postulated exposure and disease. Exposure-related risks to health can then be estimated directly from the data collected. The relationship between natural climate variability and human health has been studied using such conventional methods, supplemented with experimental studies of volunteer subjects (see, for example, Kilbourne, 1992; see also Chapter 1).

But assessment of the potential health impacts of *future* climate change concerns the *potential* effects of an *anticipated* exposure. Hence it does not follow the conventional sequence: describe, compare and infer. Rather, it asks an "if–then" question: *if* the climate changes (and if that change affects other systems), *then* what are the likely impacts on human health? Unlike conventional environmental epidemiological research, such research is not seeking new information about disease causation. Rather, it uses existing information about climate-related factors such as heat waves, infectious agents and food supplies, to forecast how a change in those factors would affect population health. The process is therefore deductive, not inductive.

In order to make such a forecast or prediction, future "unknowns" must be assumed to be an extension of present "knowns" (Levins, 1995). It must be assumed, for example, that exposure–effect relationships associated with natural variations in climate and climate-dependent systems will follow the patterns evident from previous health experiences. Thus since the fluctuation in numbers of daily deaths in relation to daily summer temperature has been documented for a number of populations, it must be assumed that the number of additional deaths that would accompany an increase in heat waves can be estimated. However, this type of scenario-based forecasting of health impacts entails unavoidable uncertainties, and surprises can be expected

Fig. 9.1. Layers of uncertainty underlying climate change impact assessment

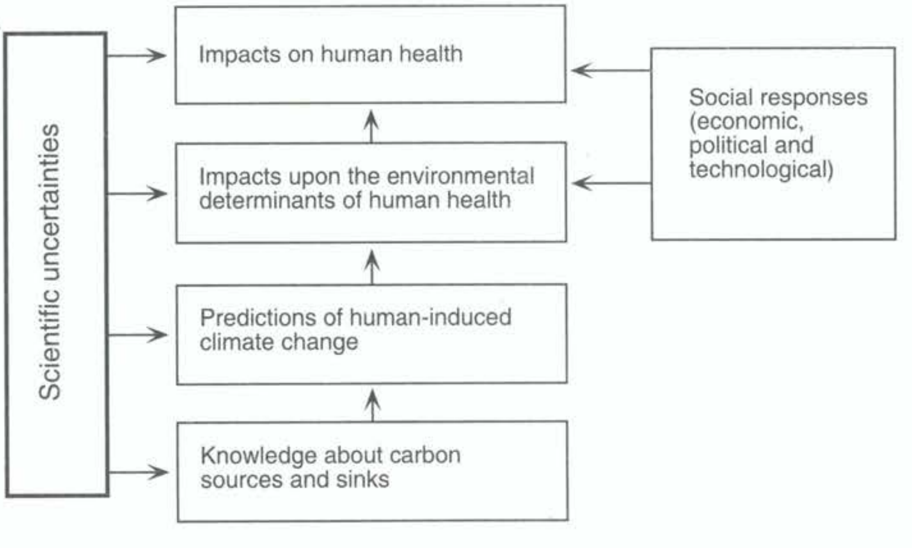
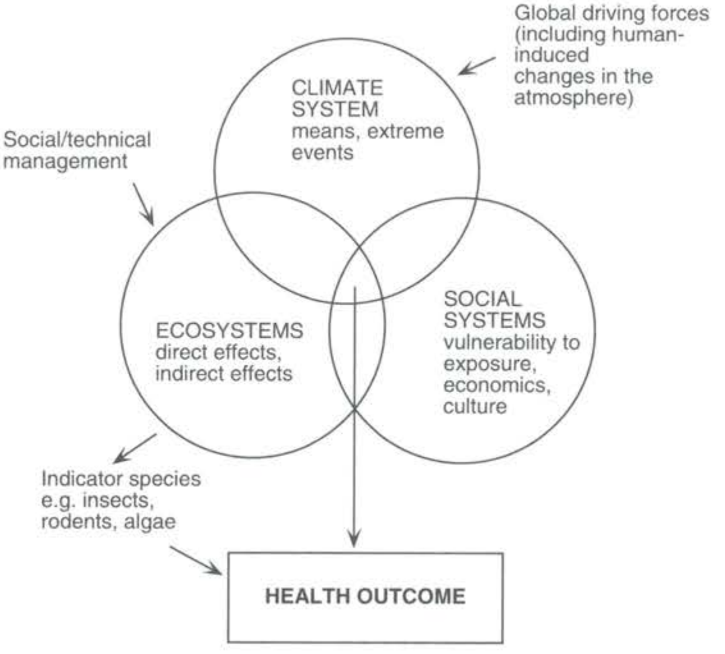


Fig. 9.2. Interactive pathways by which climate change influences health



(Levins, 1995; McMichael & Martens, 1995). The modelled scenarios of climate change themselves (particularly at the regional level) and their anticipated first-level impacts (e.g. on sea level rise, crop growth, and patterns of human settlement) are uncertain, for instance (see Fig. 9.1). Additionally, since the extent and rate of climate change, as assessed by the Intergovernmental Panel of Climate Change (IPCC) for the coming century, would go beyond the range of recorded human experience, predicting the precise range of climate change impacts on human health is not possible.

A scenario-based prediction will therefore differ significantly from prediction of, for example, lung cancer rates in 2020 in Eastern European countries, based upon current levels of cigarette smoking (Peto et al., 1994). The latter would be based on current (or directly foreseeable) exposures, the health consequences of which can be estimated from existing dose–response information. However, for many of the risks that are anticipated in connection with climate change, such as those due to changes in the range of vector-borne diseases and in levels of regional food production, empirical data referring directly to anticipated future configurations of "exposure" may be few or non-existent. Much of the assessment of the health impact of climate change therefore relies upon mathematical models that seek to predict how the relevant system (e.g. the malaria transmission system) would behave under climate change. Coping with stochastic behaviour and non-linear processes typical for such natural systems presents challenges to epidemiology with which it has little or no experience.

Assessment of health impacts on populations must also take account of the differing circumstances and vulnerability of those populations. Impoverished populations that lack resources for adaptation and protection would be much more vulnerable to some climatic impacts than would populations of wealthy nations. Population health response may thus vary in "sensitivity", i.e. in the rate of change in health outcome per unit change in climate. A "threshold" phenomenon may also apply.

For example, a certain amount of climate change may be tolerated before a perceptible health impact occurs; beyond that threshold, however, further change in climate may increase the frequency of disease or death (see Box 9.1).

A simplified diagram of the major component processes of climate change that are typically described and modelled is shown in Fig. 9.2. Global driving forces (e.g. greenhouse gas (GHG) emissions) perturb the climate system and this, in turn, affects ecosystems. This has impacts upon health, and these are conditioned by socioeconomic circumstances. This schema emphasizes the interactions between components. It also indicates that assessment of future risks to health should include monitoring of sensitive biological indicators, such as rodents or insects, that respond rapidly to changed or changing conditions (see also pages 193–196).

Health impact monitoring

The potential health impacts of climate change are wide-ranging and likely to vary in time-scale and magnitude. Ideally, monitoring will enable early detection of health impacts, or their precursor events, so that countermeasures can be implemented promptly. Monitoring should also provide early feedback for the development of health-impact predictive models.

Evidently, though, if existing health-related and environment-related monitoring systems are to monitor the health impacts of climate change, they must be modified to incorporate additional indices of change. Such indices might include organisms that carry infection (such as insects and rodents), environmentally-sensitive species (such as amphibians), and biomarkers (for example, DNA-damage predictive of cancer). On a broader scale, modification of environment-related monitoring might involve inclusion of remote sensing for large-scale monitoring of environmental and ecosystem changes (Haines, Epstein & McMichael, 1993). Meanwhile, ongoing advances in computing, geographical information systems (GIS) and telecommunications will continue to afford new monitoring opportunities.

Monitoring methods must be sensitive, specific and cost-effective. Thus the microclimatic conditions of observation sites where measurements will be taken must be sensitive to changes in global meteorology. High-altitude mountain regions at tropical latitudes might therefore be ideal. This is because they may develop local conditions under which transmission of vector-borne diseases such as malaria becomes possible. As disease-free "islands" in a sea of endemicity they could prove to be very useful indicators. Methods with high specificity are also essential so that effects due to climate change can be distinguished from those due to industrialization and population growth. Cost-effectiveness is important too since it can be used to determine whether monitoring is to be implemented as an "add-on" to pre-existing environmental monitoring systems, or established as an independent new system.

Considerable monitoring of those aspects of local environmental conditions that may affect health is already undertaken. Air and water pollution levels are measured regularly by the UNEP Global Environment Monitoring System (GEMS), for instance. Its GEMS/AIR component has been operating since 1974, in collaboration with WHO, and assesses air quality data from over 50 cities in 35 countries. Monitoring levels of pollutants in air, water and food, and identifying emission sources, are the most important means of evaluating and regulating such exposure (Osterloh et al., 1992). Comparing pollution data with exposure levels and disease surveillance

Box 9.1. Vulnerability, sensitivity and thresholds

The following examples complement the text on the concepts of vulnerability, sensitivity and thresholds, with respect to population health response to climate events:

- Heat waves and cold spells act upon human physiology and health. The body's reaction depends upon whether physiological tolerance thresholds are exceeded. Tolerance thresholds are themselves conditioned by acclimatization, health status, age, behaviour and adaptation (such as housing conditions and presence of air-conditioning). The possible synergistic effect of air pollution, which is often elevated during heat waves in cities, is a hypothetical additional conditioning factor.
- The sensitivity of health outcome response to climate change will depend on population vulnerability. The precise impact of a climate-related increase in exposure to infectious agents would depend on whether prior contact had occurred and "herd immunity" had developed, on biological resilience (itself dependent on nutritional and immune status), population density and patterns of interpersonal contact. Social infrastructure and health care resources would also condition the impact. Populations or communities most vulnerable to a specific infectious disease impact would be those with a high prevalence of undernutrition, chronic exposure to other infectious diseases, and inadequate social and physical infrastructure.
- Upper and lower bioclimatic thresholds limit the spread of many disease agents, vectors and agricultural pests. They therefore account for seasonal and longer-term fluctuations in the distribution and abundance of these organisms. The uncoupling, by climate change, of previously stable ecological relationships between species — especially predator–prey relationships, such as those between dragonflies and mosquitos — would reveal other thresholds since interspecies balances would exceed critical points. Impacts on human health due to changes in the transmission of vector-borne infections or in agricultural productivity would therefore occur as a result of a sequence or cascade of critical changes in ecological relationships.
- Vector-borne disease transmission is only possible within the lower and higher bioclimatic thresholds of the vector and the pathogen. Thus a shift in the potential habitat boundary of the anopheline vector of malaria would not automatically lead to a shift in the area of disease transmission. Specifically, the range of *Plasmodium falciparum* is limited to warm climates because this species cannot develop inside its mosquito host at temperatures below 18–20°C. Anopheline mosquitos feed and reproduce only above certain temperatures; between that threshold and a limiting upper temperature, they require less time to complete their life cycle.

These examples indicate that the vulnerability and sensitivity of human populations to the health effects resulting from climate change would vary enormously. Health impact assessment of climate change therefore requires a sound knowledge of the epidemiology and etiology of the disease entity involved, the capacity to identify the various ecological causal pathways which affect it, and understanding of the ways in which these pathways could be altered by climate change.

Sources: Curto de Casas & Carcavallo, 1984; Dobson & Carper, 1993; Gilles, 1993; Burgos et al., 1994a.

records would be an important first step towards establishing the use of indicators in environmental health policy-making, but such methodologies have only recently become the subject of study (WHO, 1993b).

Several population-based disease surveillance systems, that have operated for many years, offer good opportunities for monitoring disease trends in response to climate change or sea level rise. For example, the Matlab study population of the International Centre for Diarrhoeal Disease Research (ICDDR), in the Chandpur district of Bangladesh has been monitored by a demographic surveillance system for many years. The population of around 200 000 has formed the basis of numerous large nutritional and epidemiological studies, demonstrating the feasibility of long-term surveillance of population health in a community that is particularly vulnerable to flooding and other extreme weather events (ICDDR, 1990).

Epidemiological research: how useful in this context?

Epidemiology is the basic quantitative science of public health. It describes and seeks to explain the distribution of disease within and between populations. Its essential tasks are to identify the factors that cause or influence disease occurrence, and to quantify that causal relationship. This information can then be applied to protecting and improving the relevant population's health.

Epidemiological research is thus essentially empirical. From data about the current or recent health-related experiences of groups of people, inferences are drawn about causal relationships. This task of interpreting the present differs from that of attempting to forecast the future. Yet the question about the likely health impacts of climate change is a public health question, and one that needs to be addressed scientifically, with maximal reference to existing epidemiological knowledge of disease causation. Epidemiologists have a central role to play in addressing this question.

Limitations of conventional epidemiology

Most epidemiological research is reductionist in its approach to disease causation. That is, it seeks to identify and quantify each of the specific factors or circumstances that contribute to the causation of a disease. Epidemiologists often assume that risk factors, if truly causal, will display a quantifiable dose–response relationship to the disease under investigation: for example, the more you smoke the greater the risk of developing disease X. In reality, however, the causation of most diseases is more complex than suggested by this description.

Modern biostatistical techniques have to some extent acknowledged this complexity by fostering a more integrated approach to analysis of disease causation. These allow the "partial" effects of coexistent risk factors to be estimated, including the assessment of interactive or effect-modifying relationships between causative factors. Indeed, several mathematical modelling techniques are used to describe and explain the dynamics of infectious disease transmission. But these biostatistical techniques are predominantly descriptive and explanatory and therefore not appropriate for scenario-based predictive assessment of health impacts.

There are two main problems regarding the interface between conventional epidemiological research methods and the forecasting of climate change health impacts. Firstly, climate change health impacts refer to *future* outcomes and often with reference to a very long period of time. Yet traditional epidemiology is concerned mainly with phenomena that occurred recently or are currently occurring, i.e. resulting from recent or current exposures. It therefore seldom addresses health risks extending beyond the temporal horizon of today's generations. Secondly, the causal processes associated with the health impacts of climate change are highly complex. Most of these anticipated impacts will occur not via familiar directly-acting toxicological, metabolic and infective mechanisms, but result predominantly from perturbations of natural biogeochemical systems and impinge on whole populations rather than on small numbers of individuals. They must therefore be assessed within an ecological framework.

Integrated systems-based modelling

The complex task of predicting health outcomes of future environmental impacts requires use of integrated mathematical models (Rotmans et al., 1994; McMichael & Martens, 1995). (This is currently the only type of model available that can integrate complex relationships.) However, the use of such models to forecast health impacts remains at a relatively early stage of development; generally, these models lack regional and local resolving power, omit certain categories of variables, and have yet to be fully validated. Ideally, models should be both "dynamic" (to take account of time-related changes within the system being investigated) and "stochastic" (to incorporate the uncertainties inherent to many of the variables, expressing them as probability distributions rather than as definite values).

That said, models of the health impacts of climate change should be as simple as is both realistic and possible, particularly since the uncertainties in such models cannot be reduced by increasing their complexity. Furthermore, the assumptions and limitations of such models must be made explicit (McMichael & Martens, 1995).

Since complex systems are typically sensitive to the influence of initial conditions — as illustrated by the fact that the outcomes of various well-known climate models can vary significantly when the initial parameters are changed — accurate measurement of initial conditions is crucial. For example, the level of pre-existing immunity within the target population is an important determinant of the number of people infected by malaria. So the impact of a climate-related increase in the malaria transmission potential of the mosquito population will be less in highly endemic regions with a high prevalence of immunity, than in regions where levels of immunity are initially low.

Validation of models is important. Empirical validation refers to the concordance of the model's predictions with actual observation; this can often be assessed by "testing" the model on historical data sets. Conceptual validation, on the other hand, refers to the ideas and theoretical structures of the model and requires that these describe the perceived real world logically, and in accordance with empirical knowledge. In validating the model, a balance must be struck. If the criterion of validity is too stringent, either the model will fail (in the sense that its predictions will not agree with reality) or it will become so complex that it will not make useful predictions unless it is fed with many data, which it may be impractical to collect. However, if the criterion is too liberal, models that omit certain relationships or components, or that are based on faulty assumptions, may be adopted (Rodin, 1990).

Box 9.2. Modelling the effects of climate change on vector-borne diseases

Classical epidemiological models of infectious disease transmission illustrate the potential of vector-borne diseases to spread rapidly. Such models use the basic reproduction rate, R_0, which is defined as the number of new cases of a disease that will arise from one current case when introduced into a non-immune host population during a single transmission cycle (see also discussions of vectorial capacity in Chapter 4). Hence this rate will apply only during the initial stages of spreading, since once the population has acquired some immunity, the rate of disease spread will slow. R_0 is also a measure of an individual parasite's reproductive *potential*. The classical model shows that the equilibrium prevalence of disease, and the potential of vaccination or other campaigns to control the spread of infectious disease, depend on the value of R_0.

Predicting the value of R_0 (which provides a direct index of public health impact) is far more difficult than predicting changes in the geographical range of vectors. This is because, firstly, many different biological variables pertain to those vectors and parasites that are influenced by climatic variables, and, secondly, many aspects of human behaviour and social organization (for example, use of vector control methods) influence the probabilities of occurrence and transmission of infection.

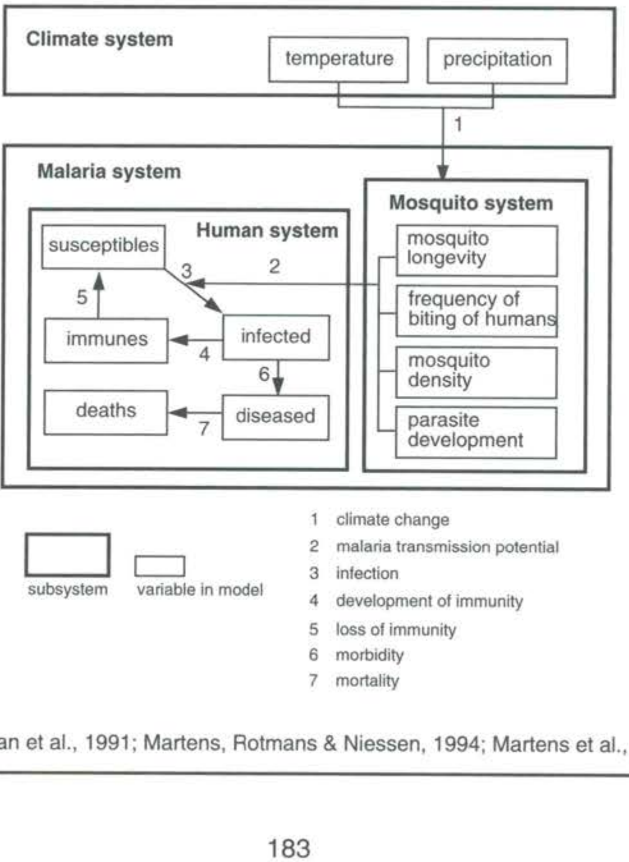
Complex relations thus exist between climate variables, vector, pathogen and human host that cannot be reduced to a simple linear relation between temperature and disease rate. Hence, the vector may spread without consequent increase in disease incidence. Conversely, a small increase in temperature may produce a marked increase in disease incidence. This has been the case In Mexico, for example, where small increases in temperature have been followed by significantly increased transmission of dengue.

An integrated mathematical model, to improve the quantitative prediction of climate-related changes in the potential distribution of malaria, was developed recently at the State Institute of Public Health and the Environment (RIVM) in the Netherlands. The model links GCM-based climate change scenarios with a module that models the relationship between climate variables and the basic reproduction rate (R_0). Although this model does not take into account all the possible determinants of malaria transmission potential, it does consider how temperature increases affect mosquito populations directly through their impacts on mosquito development, feeding-frequency and longevity, and on the incubation period of the malarial parasite inside the mosquito (see figure). Using models to estimate the effect of changes in precipitation, the availability of surface water and humidity on malaria transmission is more complex. In this particular model, lack of precipitation is therefore treated as a limiting factor for malaria transmission; a minimum seasonal average of 1.5 mm of precipitation per day was assumed necessary for mosquito development.

Since the model's predictions refer only to the potential for alterations in the geographic range of transmission, their significance must be interpreted in relation to local conditions and developments (including parasite reservoirs, mosquito densities, control measures and health services). For example, the current climate would allow transmission of *Plasmodium vivax* via locally resident mosquitos during July and August in many areas of the UK. However, well-established surveillance and preventive activities, as well as housing and land use, would, if sustained, almost certainly preclude re-introduction of malaria into the UK over the coming century.

The model used by Martens and colleagues shows a projected worldwide increase in the potential habitat of the mosquito and, hence, increased potential for local transmission of malaria (see Chapter 4). The model, despite its highly-aggregated (i.e. geographically broad) predictions and its simplifying assumptions, demonstrates the basic feasibility of modelling the impact of climate change on vector-borne diseases. Further development of such models will help to elucidate the relationships between climate change, vector population dynamics and human disease dynamics, and thus to forecast future health impacts. However, until such models have been carefully validated against historical data sets, as well as subjected to other types of reality-testing, their predictions must be viewed cautiously.

Systems diagram of a model designed to assess the impact of climate change on the potential transmission of malaria



Sources: Koopman et al., 1991; Martens, Rotmans & Niessen, 1994; Martens et al., 1995b.

Box 9.3. Mathematical modelling

Mathematical modelling seeks to represent a real world problem in terms of mathematical equations. By so doing, it can play a key role in elucidating complex systems and the consequences of changes in their component parts. For example, it is used to study infectious disease dynamics and the climate system (see Chapter 2). Models are also used as predictive tools by researchers and policy-makers.

Since complex mathematical models cannot usually be solved analytically, a computer program is needed to solve the set of equations. Several qualitative steps must be followed during the mathematical modelling process:

- problem formulation: defining the problem;
- problem analysis and structuring: defining the relevant parts of the system;
- information sampling: determining how the system's components influence each other, and collection of relevant data;
- mathematical modelling: representing the model in mathematical language;
- model implementation: translating mathematical equations into a computer program;
- program verification: checking for possible (erroneous) differences between the mathematical model and the computer program;
- model calibration: selecting parameter and initial values of variables so that the model replicates the real world as closely as possible;
- model analysis: determining the model's properties, e.g. sensitivity analyses;
- model validation: assessment of the conceptual validity (e.g. are the assumptions and scientific theories of the model valid?), empirical validity (e.g. does the model outcome reflect measured data?), and operational validity (e.g. does the model provide answers to the problem?);
- model use: begin the real application, for example, modelling the impact of an increase in temperature on a specific health-related outcome;
- evaluation of results.

There are important differences between types of mathematical model. "Dynamic" models are able to describe the behaviour of a complex interacting system over time. But in a "static" model, the variables remain constant; for example, a constant annual absolute increment in temperature is used. In a "deterministic" model the values of all parameters and time variables are known at all stages of the model, whether static or dynamic. (Models can be static or dynamic, as well as deterministic or stochastic). However, it may be neither realistic nor possible to model the real world as a deterministic one; for example, if knowledge of the true behaviour of a parameter is incomplete. A "stochastic" model, in which certain parts of the model are represented as probability distributions rather than as specific values, may therefore be preferable.

Mathematical modelling requires a variety of techniques. One of the major pitfalls in mathematical modelling is a failure to document the model properly, with the result that the assumptions and limitations of the model are obscured. It is also possible to forget that the model is a simplification of the real world, and not an identification. In modelling (global) environmental problems, the aim should be to produce the simplest adequate model. The uncertainties inherent in modelling cannot be reduced by increasing the complexity of the models.

Sources: Janssen et al., 1990; Murthy et al., 1990.

Epidemiological surveillance techniques

Epidemiological surveillance is used to follow trends in disease over time and to identify disease outbreaks. The data collected can be used to determine where preventive or curative approaches are likely to be most beneficial, where more research is needed, and to assess the impact of control measures. Although traditionally used to follow infectious diseases trends, epidemiological surveillance can also be used to follow trends in non-infectious diseases such as skin cancer.

Advances in telecommunications technology now make it possible to monitor disease incidence at many geographic sites at once and to coordinate data collection. Indeed, a group of directors of WHO Collaborating Centres recently issued the "Shanghai declaration" requesting nations "to consider the development of scientifically-based national non-infectious disease plans" and stating that "standardized cost-effective integrated disease monitoring systems" should form the basis of these plans (WHO Directors of Collaborating Centres and Key Officials, 1993).

Disease telemonitoring systems are just one example of how telecommunications technology is being applied for disease surveillance and monitoring. A disease telemonitoring system might include a local disease identification centre, such as a hospital, primary care centre or laboratory, linked, via a personal computer and modem, to a national or international centre. Such a system enables continuously updated data to be compiled for individual sites and to be aggregated as appropriate, and facilitates early investigation of changes in disease incidence.

Existing international networks, for example, ProMED, are based on communications through the Internet. Such communications networks could also be used in the monitoring of the impacts of climate change. A variety of long-range digital data links, covering a distance from 1–1000 miles, using radio frequency media, and without need of a costly satellite interface, are currently in operation. They rely on HF, VHF and UHF frequencies which are authorized by the relevant Department or Ministry of Telecommunications. Other more costly systems rely on signals repeating on either orbiting or stationary satellites and permit high-speed data transfer. Orbiting satellite systems are timed for data transfer as the satellite passes overhead and are therefore not available 24 hours a day. If a public telephone line is available, local disease monitoring centres can use a range of technologies to establish electronic mail links with the Internet. Clearly, data must be of high quality. Issues such as accountability and confidentiality must also be addressed (Giesecke, 1995). An international coordinating centre would ensure that standards are consistent when used within and between individual countries. Such a centre would also have an important role in the area of information management and training, and could provide free-of-charge or low-cost software.

A simple international disease-counting protocol (i.e. a standard for disease registration) could form the basis of the information needed for rapid and accurate counting of cases (La Porte et al., 1993). If the data collection for such a system could be integrated into widely available hospital and primary care computer systems that can be used for other clinical purposes such as writing prescriptions and recording of data on preventive activities, the systematic entry of relevant diagnostic data would be encouraged. For instance, it has been shown that a large commercial primary care computing system used by general practitioners in the UK accurately records incidence of psychotic illness (Nazareth et al., 1993). Large numbers of general practices use the system to record diagnostic information relating to more than 90% of consultations that result in a prescription (Jick, Jick & Derby, 1991).

Considerable investment in the standardization of diagnosis and recording is essential if the reliability and validity of diagnostic data are to be assured. A weekly information return service at the UK Royal College of General Practitioners, first established in 1967, operates by taking weekly extracts of new episode data from the diagnostic indices of medical practitioners. It is structured so that analysis can be made by person, by episode, or by doctor–patient encounter, and has formed the basis of major general practice-based national morbidity surveys (Fleming, Norbury & Crombie, 1991).

However, complete enumeration of cases of particular diseases may be difficult, either because of lack of a universal registration system, mobility of the population in question, or use of multiple health facilities by individuals. But capture–recapture approaches that have been used to develop estimates of animal populations can be modified and applied to human populations. In order to estimate the number of fish in a lake, a given number of fish are caught, tagged and released. On subsequent days fish are caught again and the number of tagged individuals noted. The total number of fish in the lake can then be estimated based on the proportion of fish recaptured. In the case of human populations, multiple data sources can be examined to obtain formal measurements of the degree of undercounting among individual sources and to adjust estimates of the size of the population to take this undercounting into account (La Porte, 1993). Such techniques have been used to estimate the size of human populations that are difficult to reach (McKeganey et al., 1992; Fisher et al., 1994).

Assessing health impacts within an ecological framework

The need for an ecological framework

A previous section in this chapter demonstrates that the health sciences are not well adapted for analysis of disease causation involving combinations of environmental factors that interact with one another, influence feedback loops, and that are themselves parts of complex systems influenced by human interventions. Nor are the empirical sciences able to deal with the uncertainties arising from such complex systems and the predictive modelling of them (McMichael & Martens, 1995; Patz & Balbus, 1996).

Recognizing these problems, various scientists in the Soviet Union in the early part of this century attempted to elucidate the complexities of environmental determinants of infectious diseases by identifying and describing landscape classes that carry a specific degree of transmission risk (see, for example, Beklemishev, 1947; Lysenko & Dang Van Ngy, 1965; Pavlovsky, 1966). This approach has contributed to the environmental management of some zoonoses and vector-borne diseases, particularly with reference to large-scale agriculture and forestry development schemes, and the stratified planning of country-wide disease control schemes. Even so, "landscape epidemiology" did not win much recognition outside the former Soviet Union until the recent development of remote sensing and GIS technologies resolved many of the complications of large-scale data collection and analysis (see Box 9.4).

It should also be borne in mind that most of the relevant "landscape" characteristics, i.e. the ecosystem-based determinants of health and disease, are themselves subject to change. Thus today, landscape characteristics are being influenced by the same human factors that are affecting radiative forcing in the atmosphere. Deforestation through burning — which occurs on an immense scale

Box 9.4. Remote sensing and geographic information systems

In principle, remote sensing encompasses all methods of observing objects or phenomena from a distance. In recent years, however, it has been defined as a method for observing Earth's surface with the aid of instruments, such as optical instruments or radar, mounted on satellites or aeroplanes. Geographic information systems (GIS) are advanced computer-based systems for the integrated analysis of different sets of geographically-referenced data. Remote sensing and GIS are increasingly used in combination to study the distribution of vegetation types, pests, geological features, water bodies and soil moisture, land use and human settlements, and the epidemiology of animal diseases.

Several countries, including China, France, India, Japan and the USA, have developed and launched sophisticated remote sensing systems (see also Table 9.1). The satellites and the instrument systems they carry differ with respect to the spatial, spectral and temporal resolution of the data they collect, the swath width (i.e. the width of the strip of land covered by the passing satellite) and the turnaround time. The principal uses of remote sensing in the various spectral regions are listed in the table below. The resultant products, which include data sets and photographs, are finding a growing market in agriculture, forestry, mining and urban planning.

Remote sensing and GIS are also used for human disease monitoring and surveillance. Typically, remote sensing data first assist in the identification of habitats that foster high survival rates for disease vectors such as ticks, tsetse flies and mosquitos. Subsequent GIS analysis of vector habitats, against demographic data and land-use patterns, can establish the geographic patterns for human risk of infection. For example, visible red and near infrared spectral regions (from AVHRR) are combined to produce the Normalized Difference Vegetation Index (NDVI) which correlates with photosynthetic activity of plants, precipitation and saturation deficit (a measure of the drying power of air); these environmental factors determine tsetse fly survival. It has been shown that NDVI can be used to predict tsetse fly abundance, and even the incidence and prevalence of human African trypanosomiasis. Other diseases that have been mapped using remote sensing/GIS include malaria and Lyme disease.

Spectral regions in which visible–infrared remote sensing data are typically acquired and their principal applications

	Principal object of measurement/mapping	System*
Blue	Salt-water intrusion, soil hydrology, forest types	TM
Green	Green reflectance peak in vegetation; plant vigour assessment	TM, MSS, XS
Red	Chlorophyll adsorption; vegetation type	TM, MSS, XS, AVHRR
Near-infrared	Vegetation type, density, biomass content; water absorption and soil moisture	TM, MSS, XS, AVHRR
Mid-infrared	Vegetation moisture content and soil moisture content	TM
Thermal	Vegetation stress analysis and soil moisture discrimination	TM, AVHRR

* TM = thematic mapper; MSS = multispectral scanner; XS = SPOT multispectral; AVHRR = advanced very high resolution radiometer

Sources: Cibula, 1976; Hayes et al., 1985; Linthicum et al., 1987; Hugh-Jones, 1991; Rogers & Randolph, 1991; Glass et al., 1993; Rogers & Packer, 1993; Rogers & Randolph, 1993; Rogers & Williams, 1993; Washino & Wood, 1994; de Savigny & Wijeyaratne, 1995.

in some regions of the world, such as the Brazilian Amazon — is a good example. It results in a redistribution in the water balance of the regional and global atmospheres, and reduces the water absorption capacities of soils, particularly if it occurs in tropical areas. It also leads to a reduction in the size of rodent and pest predator populations through elimination of vegetation cover. Each of these factors may affect agricultural production adversely. Human health may then suffer following declines in crop yields, increased use and abuse of pesticides, and increased transmission of certain diseases due to increases in populations of, for example, rodents, that serve as vectors. Furthermore, since biomass burning is a major source of carbon dioxide (CO_2) and other GHGs, and forests are a major carbon sink, deforestation contributes to GHG accumulation in the atmosphere and potential climate change, which could have additional but quite different human health effects.

This example illustrates that the human health effects of climate change must be assessed within the context of other coexisting environmental changes, including: rapid urbanization and increasing human population density; increasing human mobility; increasing movement of produce and products; desertification; depletion of aquifers; pollution of water, air and soils, and loss of biodiversity. Each of these influence health through various pathways, and many of them interact. Indeed, the combined action of many causal factors may produce "nasty synergies" that promote environmental conditions leading to ecological discontinuities, with serious consequences for human health (Myers, 1994c).

Not all of the environmental changes associated with climate change will have *significant* effects on health, however. There may be difficulties in distinguishing between climate-related environmental factors that do affect health and those that are merely associated with the climate and health relationship. In reality, however, many important determinants of human population health are themselves the result of complex human actions, including those that affect climate. Under such complex circumstances, apportioning "causation" between coexistent environmental influences is an almost impossible task — and may overlook the synergistic effects described above.

Ecologically-based human health risk assessment

Infectious diseases are the most obvious example of a category of health problem with complex climate-related, ecologically-based dynamics. This section uses the example of infectious disease to explore such dynamics and to examine the scope for ecologically-based risk assessment.

Ecologists have clarified the subtle and complex ways in which the life cycles and population dynamics of infectious agents are influenced by ecological conditions. In view of the relative stability of climatic conditions, they have tended to focus on the influence on transmission cycles and infection of natural variation in factors such as temperature, humidity, seasonality and extreme weather events. But this focus broadened with the advent of concern — first expressed by Carson (1962) — about the insidious consequences of large-scale human intervention in natural systems. Carson foresaw that the indiscriminate use of chemicals in the form of pesticides and herbicides would disturb ecosystems and upset predator–prey relationships, thereby potentiating the escape of pathogens and pests from natural biological control processes. Such concern has grown considerably and with it understanding of the complex ways in which climate change could affect human infectious disease transmission.

Box 9.5. Potential impacts of climate change on ecosystems

Species that are "*r*-strategists" have a small body size, grow rapidly, and invest energy in producing large numbers of offspring to ensure their species' survival. In contrast, "*K*-strategists" have a large body size, develop slowly, reproduce at lower rates and have a greater capacity for organism repair. But they are also less sensitive than *r*-strategists to subtle negative feedback mechanisms that ensure that population densities do not exceed the maximum sustainable level. It follows therefore that *r*-strategists have a greater capacity to deal with rapid environmental change than *K*-strategists — provided the new environmental conditions do not fall outside their range of tolerance. Multiple and sudden stresses in ecosystems therefore typically result in the rapid multiplication of the most versatile and adaptive *r*-species, such as insects, rodents, weeds and phytoplankton.

The following are examples of ecosystem stresses that may affect human health indirectly through the creation of a comparative advantage for *r*-strategists:

- Some species of flora and fauna would be unable to migrate or adapt to climate change, in part because of constraints imposed by non-climate variables such as day-length, geographical barriers, or soil type.
- The additional stress of climate change is likely to accelerate the extinction rate of species. This often involves the loss of top predators within a local ecosystem, with a resultant increase in the *r:K* ratio among remaining species.
- Climate change may have different impacts on species at different trophic levels within the food web (e.g. primary producers, herbivores, carnivores or top carnivores).
- Decline of environmental "specialist" species (that is, species with small ecological niches), with or without concurrent increase of generalist and opportunistic *r*-species.
- Subtle changes in climate may have major impacts on ecosystems where conditions are close to a threshold level.
- Changes in soil moisture content and nutrient levels.
- Synchronous disturbances between mutually dependent species (e.g. predators and prey, hosts and pathogens).

Predator–prey relationships are obviously important in maintaining the natural control mechanisms operating in populations of pests and pathogenic microorganisms. Understanding the interdependencies between ecological checks and balances, and environmental factors, is crucial to assessment of the infectious disease impacts of climate change. Some climate-driven changes can be appreciated only by examining how climate affects ecological dynamics. For example, droughts may reduce the numbers of predators (such as owls and snakes) and of small mammals (such as rodents), with subsequent heavy precipitation causing population explosions of the latter. Heavy precipitation related to the El Niño/Southern Oscillation may thus have contributed to outbreaks of new and emerging rodent-borne infectious diseases in the USA and in Southern Africa.

Sources: Krause, 1992; Levins et al., 1993; Epstein & Chikwenhere, 1994b; Mirsky, 1995.

Box 9.6. Environmental change and health: case study of Honduras

Honduras is a mountainous, tropical country with a population of 5.5 million. Its tropical ecosystem is suffering accelerated destruction due to economic and social policies that do not take sufficient account of environmental concerns. These policies are altering biodiversity and favour environmental changes that contribute to increased risk of disease transmission by insect vectors and via contaminated water. Adverse public health impacts have been observed following increases in deforestation, overgrazing, monocultural farming and pesticide abuse. Other factors, such as increases in external debt, and reductions in health and education budgets, have also jeopardized the health of vulnerable segments of the population.

Between 1964 and 1990, Honduras lost 34% (26 000 km^2) of its pine and deciduous forest through logging, military construction and the use of wood as fuel. Deforestation continues at the rate of 80 000 hectares annually. Deforestation has directly affected the availability of fresh water. It has also increased erosion which has increased vulnerability to climate extremes. Heavy rains often cause flooding and landslides. This sort of local environmental change will increase the vulnerability of populations to the impact of global climate change. Specific examples of the impact of environmental change on public health are given below.

- *Malaria:* In southern Honduras, desiccation and soil erosion caused by forest clearance, cattle grazing, and intensive cultivation of sugar cane and cotton, have altered the regional hydrological cycle. The sustained increase in ambient temperature has made this region too hot for anopheline mosquitos and the incidence of malaria has declined. However, this semi-desertification has forced people to migrate to cities, plantations and assembly plants further north. Large areas of tropical rain forest in the north east (La Mosquitia) have been cleared and the migrants who have concentrated there tend not to be immune to malaria. Furthermore, the indiscriminate use of pesticides in the cultivation of bananas, pineapples and melons has led to widespread anopheline resistance.
- *Chagas disease:* Deprived of habitat and food sources, the reservoir hosts (opossums, armadillos, cats and dogs) and insect vectors of American trypanosomiasis have moved to the peri-urban "misery belts". In 1992, 24% of the residents in endemic areas were seropositive for this disease and in the capital, Tegucigalpa, 45% of the vector triatomine bugs that were sampled were infected with the *Trypanosoma cruzi* pathogen. Blood transfusions are now one of the principal routes of Chagas and malaria transmission in Honduras.
- *Leishmaniasis:* The life cycle of the *Leishmania* pathogen involves sandflies, rodents and dogs. Intrusion into Honduran forests by road builders, and by refugees and troops from Nicaragua, El Salvador and Guatemala, has led to an increase in cutaneous and visceral forms of leishmaniasis.
- *Food productivity:* Over 60% of Honduran children under 10 years of age suffer from at least grade I malnutrition (Gomez classification). The loss of staple crops to vector-borne plant pathogens is further stunting their growth and development, and reducing their immunity to disease.

Sources: Matola, White & Magayuka, 1987; data from Honduran Ministry of Health, 1992; Almendares, 1993; Walsh, Molineaux & Birley, 1993; Visser, 1993; Minister of Health of Honduras and PAHO, 1994.

Conventional quantitative risk assessment, however, particularly as applied to assessment of the toxicological risks arising from environmental chemical exposures, is not well adapted to assessing how environment and a particular ecological context influence the transmission of a specific infectious disease. This is because conventional quantitative risk assessment assumes an underlying discrete and mechanistic causal relationship, as can be summarized in a dose–response graph, which, when combined with knowledge about a population's exposure to a particular chemical, purportedly enables direct estimation of health impact. In contrast, adopting an ecological risk assessment approach permits evaluation of multiple ecological stress factors and their impacts on a variety of species within an ecosystem (Risk Assessment Forum, 1992). Ecological risk assessment is therefore better adapted to assessing non-chemical "climatic hazards", for which dose–response relationships are generally less meaningful.

Consideration must also be given to the fact that the magnitude of climate change *per se* may not be the determining factor in terms of human health outcomes. Various intervening impacts on biological systems (such as arthropod-vector habitats or marine vegetation) or on physical systems (such as the hydrological cycle) may mediate the impact of climate change on human health. Furthermore, climate variability, frequency of extreme events, rate of change, or timing of climate events may be more damaging to an ecosystem than an absolute increase in temperature. This means that, within the context of climate change, the concepts of "hazardous exposure" and "exposure dose" may not be applicable. It may be more useful instead to consider ecological "stressors" since these better describe the magnitude, nature and temporal aspects of climate change. The term stressor, in place of "hazard", affords a broader accounting of the processes that can disrupt ecosystems (and therefore serve as early biological indicators) and that may affect human health (see pages 194–195).

Illustrations of the complexities of health impact assessment at a national level, where climate-related health effects combine with impacts from vast environmental changes more directly related to the development process, can be found for developed and developing countries alike. Box 9.6 describes just such a situation in Honduras. This example illustrates both the health and environmental effects of local climate change, and the increased vulnerability to global climate change of areas that have undergone sustained environmental degradation.

Evidently, the ultimate goal of impact assessment is to identify interventions, in the form of prevention, mitigation and adaptation, that will produce the most health improvement for the smallest economic outlay. Interventions would include generalized defences against disease emergence, such as biological control of pests and vectors by means of natural predators, and programmes to reduce environmental and social vulnerability to disease and climatic extremes.

Monitoring the health impacts of climate change

The close relationship between health impact research and monitoring was described earlier (see page 175). Many research questions may arise from the monitoring of disease and climate. Likewise, research may indicate diseases and populations for which monitoring is required, and contribute to advances in monitoring methods and technologies.

In order to integrate health monitoring data with climate and ecological monitoring, regional application centres will need to be established. Such centres would have applications not only for the health sector, but also for the agricultural, fisheries, energy and industrial sectors. They could also contribute to the creation of public health early warning systems.

In particular, analysis of climate-induced human health impacts will require the superimposition of geo-referenced data on vegetation, land use, disease incidence, demography, vector dynamics, climate and weather on GISs (see Box 9.4). GISs have a vast potential regarding the development of timely, environmentally sound, public health interventions, and improvement of predictive modelling of health impacts. However, an international survey carried out under the auspices of the International Geological Correlation Programme and UNESCO suggested that for some countries, restricted access to conventional map data sources has slowed progress in this area (Shennan, 1993). Access may be restricted due to lack of resources (for purchasing and processing), or because data are not made available by their owners.

Changes in health risk or health status should be monitored for populations around the world, especially in areas that are deemed particularly vulnerable to the health effects of climate change. Wherever feasible such monitoring efforts should be integrated with existing surveillance systems established for certain infectious disease categories. Regrettably, infectious disease surveillance systems have become weakened in many countries during the past ten to twenty years.

Appropriate health-related end-points, such as disease-specific mortality and morbidity, selected on the basis of empirical observations and theoretical considerations of ecological processes that are likely to be altered by climate change, should be used for monitoring. Additionally, where possible, measurable intermediate biological indicators such as vectors or reservoirs should be identified and incorporated into monitoring to improve the sensitivity of human health risk assessment. For example, the response of vector-borne diseases to climate change will depend on the existence of vectors, reservoir and intermediate hosts, and their natural enemies, whose ranges are defined by climate variables. Changes among the more sensitive "intermediate" species in a human disease transmission system (see Box 9.7 and pages 193–196) are likely to occur far earlier than changes in actual disease incidence or prevalence. By monitoring such precursor changes, therefore, underlying climate impact models may be validated and refined, and opportunities for early interventions identified.

Direct impacts and seasonal variations

The simplest direct effects of temperature on health relate to mortality and can be best detected by analysing daily mortality data: for example, short-term alterations in the death rate among the elderly and the sick during periods of high and low temperatures. (Aggregation of deaths into weekly or monthly statistics is of much less value because irregularities tend to be smoothed out.) In developed countries most of the data required for this type of analysis are readily available. But they are often lacking in less developed countries, particularly with respect to urban centres.

Changes in morbidity and in seasonal disease patterns also indicate the direct effects of temperature on health and can be detected in primary care data collected from sentinel sites, such as those maintained by general practitioners in the UK (Fleming, Norbury & Crombie, 1991). The data collected demonstrate, for instance, that consultations for asthma have risen in recent years, albeit for reasons that are unclear, and that they show seasonal variations, with peaks in the summer and towards the end of the year.

Natural disasters

Climate change could alter natural disaster variability and frequency (see Chapters 2 and 6). As a result, natural disaster impacts on human population health could become more severe (see Chapter 6). Monitoring the occurrence and severity of natural disasters already constitutes an important tool for disaster and emergency management. However, assessment of the human health effects of these events is usually limited to injuries and deaths caused directly by the disaster, with little attention paid to infectious disease outbreaks, starvation or psychological disorders that may occur in its aftermath.

Natural disaster databases

Several databases have been established to meet the information needs of government emergency management agencies and nongovernment organizations active in this field. Most of these databases record national or regional disaster data. The typical data sets registered include information on the type of disaster, the date, the locality, number of deaths and number of injured. Additionally, information may be included on disease outbreaks, or the kind of response activity undertaken, and the resources made available for relief and recovery. Databases often share information obtained, but little effort has been made to standardize definitions and outputs. Nevertheless, several of these databases offer scope for the continuous global monitoring of natural disasters and their implications for human health.

A method for building a global disaster database for measuring disaster impact and losses to life and health has been developed by the Network for Social Studies on Disaster Prevention in Latin America (LA RED), in Lima, Peru. The information system, which is known as DesInventar, permits the use of standardized data management systems, and facilitates analysis and graphic representation of data on disasters. DesInventar has the following characteristics:

- it is a database of disasters rather than of hazardous events;
- it registers information on all disasters with a measurable social, economic or physical impact and not just those of large disasters;
- it uses precise definitions for types of impact and effect;
- it defines the locality of disasters on the basis of the smallest political-administrative unit of the country affected.

So far, DesInventar has been used by LA RED to build up a regional database covering disasters that occurred between 1990 and 1995 in nine Latin American countries. The database will be made available in 1996 on CD-ROM and progressively extended to include other countries in the region.

Ecosystem health

Changes in the distribution and biological activity of organisms, while often resulting from environmental stress, could provide early evidence of climate-related shifts in human health risks. Several approaches based on the use of indicators offer promise for measuring environmental stress. Some models that have been constructed to link particular stressors to their likely effects, such as the impacts of contaminants or acid precipitation on fish populations, could be used to monitor ecosystem stresses that have the potential to become direct risks to human health (Haux

& Forlin, 1988; Minns et al., 1990). However, many ecosystems suffer from multiple stresses and there is a need, therefore, to develop broadly defined indicators (i.e. indices) that enable ecosystem functioning to be monitored. (Ecosystem monitoring can be defined as monitoring of ecosystem components and processes, such as species composition, vegetation structure, photosynthesis and carbon absorption rates, and pollution levels.) The concept of ecosystem "health" has been proposed as an integrative measure for the status of an ecosystem, implying that ecosystems in "bad health" pose a risk to the health of species, including humans (Rapport, 1992). There is as yet no agreed standardized method for measuring ecosystem health status, although several integrated impact models have been proposed.

The AMOEBE model, for instance, involves determining reference species "complexes" (usually composed of 32 species) considered representative of a given ecosystem, and subsequently monitoring the populations of these species to determine to what extent the defined complexes remain representative (ten Brink, Hosper & Colijn, 1991). Deviations from baseline densities, or the extent to which these densities deviate from predefined managerial standards, are taken as a measure of the condition of the whole ecosystem. This method, currently applied to ecosystem management and nature conservation, can also be adapted for monitoring ecosystems critical to the survival of human pathogens or their vectors. It is an integrated model in that it examines systems rather than single system components.

MOVE is another multiple-stress model. Based on integration of a soil module and a vegetation module, it can be used to predict the impacts on ecosystems that could be anticipated under different environmental scenarios (Latour, Reiling & Slooff, 1994). Integrated ecosystem impact modelling is at an early stage of development though. Further work in this area should be encouraged, in particular to explore the potential of ecosystem models for early detection of changes in species dynamics. The latter would facilitate prediction of infectious disease hazards.

In many instances, disease outbreaks are symptoms of ecosystem dysfunction. In fact, they are often the first recognized impacts of an environmental stress. In this context, potential "marker" species that are relevant to human health and well-being include insect and rodent intermediate hosts, and reservoirs or vectors of viral, bacterial, rickettsial and parasitic diseases (Epstein, 1995b). Since they are cold-blooded, have short generation times and are environmentally hardy, insects are relatively climate-sensitive biological indicators for terrestrial ecosystems. Rodent populations — in urban and arid rural settings — also respond rapidly to environmental change such as decreases in populations of natural predators. In coastal marine systems, ecological indicators relevant to human health include phytoplankton populations. The emergence and abundance of toxic phytoplankton species may reflect changing environmental conditions, such as warmer sea surface temperatures and, in freshwater systems, increased availability of carbon dioxide for photosynthesis (Rosenberg et al., 1988; Saunders, 1988).

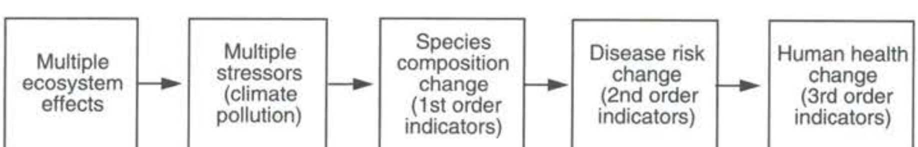
Thresholds above which damage occurs, and optimum ranges for biological parameters such as maturation and development, longevity, or reproduction, also respond to climatic conditions and so can be used as quantifiable indicators of ecosystem functioning. The biological response of a species to a climatic factor that exceeds that species' threshold may be cumulative, or even exponential, depending on the dose–response curve. But for complex ecological disease systems involving many species, determining threshold levels on the basis of conventional dose–response relationships will not be possible until a measure has been agreed for describing ecosystem health. Ecosystem thresholds may be conceptualized as quantifiable levels at which certain ecosystem

Box 9.7. Ecosystem-based human health risk assessment

Traditional environmental health risk assessment is a quantitative, partly empirical and (sometimes) partly speculative process that starts by identifying a discrete health "hazard", subsequently characterizes the resulting health "risks" in terms of dose–response relationships, then assesses likely human "exposure" levels to these risks, and concludes by estimating the likely disease implications. This method has helped establish agreed acceptable exposure levels and target values for ionizing and non-ionizing radiation, and for toxic chemicals, such as those reviewed regularly by the International Programme on Chemical Safety.

Such approaches may not be appropriate, however, if the health risk concerned is linked to an ecological phenomenon or entity, such as weather variability, sea level rise, freshwater availability, agricultural productivity, livestock populations, disease reservoirs or vectors. Inasmuch as these ecological factors are climate-dependent, the potential impact on human health of the relevant risk is probably the outcome of several simultaneous stressors such as climate extremes, pollution, deforestation, or desertification, or at least mutually-connected processes, each of which is characterized by an unknown degree of uncertainty both as to its qualitative nature and its dose–response relationship. Some form of ecosystem-based human health risk assessment is therefore needed to contribute to the forecasting of such risks and/or enable early warnings to be issued. The starting point should be the notion that multiple stressors will produce multiple ecosystem effects, which in turn will lead to early changes in species composition. While these changes may not be of direct consequence to human health, they could "signal" the advent of changes in populations of species that are important as either vectors or agents of human disease.

Early changes in species composition are targeted by ecologists as first-order indicators of impacts on ecosystem impact due to stress (see discussion of AMOEBE and MOVE approaches, page 194). For health risk assessment purposes, first-order indicators (such as decimation of food plants during prolonged droughts) should be identified that can serve to predict subsequent population effects in species of indirect (e.g. rodents, mosquitos) or direct (e.g. cyanobacteria, legionellas) consequence for human health — the second-order, or "target" indicators. Finally, traditional epidemiological monitoring and surveillance will render early warning signals, or third-order indicators of epidemic activity, apparent.



The predictive power of first-order indicators will be limited by the degree to which the original multiple stressors and the multiple ecosystem effects themselves contribute to changes in the disease risk. Thus first-order indicators have no contribution to make to prediction of the direct effects of climate stressors such as heat stress mortality.

Source: WHO, 1989.

parameters such as biodiversity start to behave non-linearly. Non-linearity may indicate that climate-related changes in human disease is occurring in areas that previously were unaffected.

In certain wildlife populations, health conditions may serve as biological indicators of biologically significant environmental changes. For example, an unusual increase in mortality in New Zealand penguins during the summer of 1989–1990 was attributed to an atypical sea surface temperature of 15.4°C, compared to the more usual 11°C (Gill & Darby, 1993). Graczyk et al. (1995) pointed out that any temperature increase in the area (Otago Peninsula) would have favoured the observed increase in populations of *Culex quinquefasciatus* (vector of avian malaria).

Parallels have been drawn between attempts to assess ecosystem health and methods for assessing human health and detecting of early signs of disease (Rapport, 1989). Three core groups of indicators have been outlined:

- screening indicators: these give early indications of stress within an ecosystem;
- diagnostic indicators: these help to determine probable causes;
- indicators that reflect overall functioning, or "health" of ecosystems (Rapport, 1992).

Most progress to date has been made in identifying screening indicators. General screening indicators include changes in species diversity, productivity and nutrient cycling; use of them can be supplemented by use of sensitive indicator species. Less is known about diagnostic indicators. This is partly because the taxonomy of ecosystem ill-health is at an early stage of development. Complexity is increased by the consideration that different stresses on an ecosystem may lead to the same outcome, and that, conversely, single stresses may have different effects depending on the susceptibility of the ecosystem in question. Furthermore, the feedback mechanisms that maintain the integrity of healthy ecosystems are poorly understood. Clearly, the concept of ecosystem health and its relevance for human population health requires further study and development.

Large marine ecosystems and sea level rise

The main components of large marine ecosystem monitoring are summarized in Box 9.8. Given the range of disciplines involved, close coordination is necessary to ensure that data collected by, for example, meteorologists, environmental protection agencies, marine biologists and ministries of health, is fed into a central monitoring system.

Sea surface temperatures can be monitored via satellite remote sensing. Microwave bands used for measuring salinity may also be helpful for identifying and monitoring toxic phytoplankton species. Monitoring using remote sensing will improve further with application of new technologies, such as the Sea-viewing Wide-field-of-view Sensor (SeaWiFS), a space-borne ocean colour scanner. However, current monitoring techniques cannot provide sufficient information on individual species. They should therefore be supplemented with local sampling of, for example, individual species of phytoplankton and zooplankton associated with gastrointestinal pathogens (such as cholera) and biotoxins (which cause fish and shellfish poisoning) (Epstein, Rogers & Slooff, 1993).

Data on winds and currents, and levels of nutrients (including nitrogen and phosphorus originating from sewage), fertilizers and industrial pollutants, will help determine when conditions are

Box 9.8. Large marine ecosystem monitoring

Integrated monitoring of large marine ecosystems to facilitate early detection of human disease risk should include elements of the following four categories:

Meteorology	• Storms, sea surface temperature, winds, currents
Remote sensing	• Algal blooms, sea surface temperatures
Sampling	• Shellfish (to estimate potential biotoxin contamination) • Phytoplankton: species composition and associated pathogens • Coral reef conditions (affected by algal mats causing local hypoxia) • Essential nutrients, nitrogen, and phosphorus levels due to soil erosion, discharge of sewage, fertilizer run-off, etc.
Epidemiology	• Cholera outbreaks in tropical zones • *Vibrio cholerae* non-01, *V. vulnificus,* and *V. parahaemolyticus* outbreaks in tropical and temperate zones • Outbreaks of shellfish poisoning (PSP, DSP, ASP) in temperate zones • Outbreaks of fish poisoning: ciguatera, histamine-scombroid and puffer fish poisoning in tropical and temperate zones

propitious for the growth of algal blooms (Epstein, Ford & Colwell, 1993). Algal blooms are harmful to marine life (see Chapter 4) and can act as reservoirs for certain pathogens. They sometimes also serve as an early warning signal for potential shellfish poisoning in humans. Local sampling and bioassay are currently the only methods available for monitoring the presence of toxic phytoplankton. Such monitoring has proved effective in preventing shellfish poisoning in developed countries and should also be implemented in less developed countries (Tester, 1994).

Monitoring of large marine ecosystems, funded by the Global Environment Facility, is scheduled for the Gulf of Guinea, then the Yellow Sea, and ultimately the world's other 49 coastal marine ecosystems (Sherman, 1994). This environmental monitoring should be supplemented with epidemiological surveillance of coastal communities for incidence of diseases such as cholera and cases of fish (such as ciguatera) and shellfish poisoning. Monitoring both the marine environment and human health in coastal areas should facilitate selection and implementation of public health measures designed to mitigate or prevent human health effects arising from the impacts of climate change on the marine environment.

Monitoring of sea level rise is another major component of marine ecosystem monitoring. The Global Sea Level Observing System (GLOSS), which has a tide-gauge network of about 300 stations, provides data on sea level rise, as well as information on ocean circulation patterns and climate variability. Data collected by GLOSS are used to calibrate satellite altimeters. Measurements taken by the latter are becoming increasingly accurate (Warrick et al., 1996). As for the future impact of sea level rise on coastal lowlands, GIS may prove to be a unique tool for risk assessment and impact monitoring of coastal areas, based on all available georeferenced information.

Fresh water

In terms of human development, fresh water is fast becoming a limiting factor; demand for safe drinking-water already exceeds supplies. Depletion and degradation of rivers, lakes and underground aquifers is now widespread. In twenty-six countries, indigenous water supplies amount to less than 1000 m^3 (a common benchmark for chronic water scarcity) per person per year. By 2000, around 300 million people in Africa, one-third of that continent's projected population, will live in countries suffering from water scarcity (Postel, 1992). Globally, the expansion of irrigated areas, which currently produce one-third of the world's food, has slowed to about 1% per year, while annual world population is currently growing at a rate of 1.7%. Yet water quantity is not monitored globally.

Most countries do, however, monitor the flows of rivers and the levels of lakes that fall within their national boundaries. Additionally, the Global Runoff Data Centre, under the auspices of WMO, maintains a database on daily river flows into which data is fed from several thousand measuring stations in almost one hundred countries, and from other sources such as satellites and weather stations. As the hydrological cycle is a sensitive indicator of the impacts of climate change, information about changes in run-off can be used to calibrate and validate output obtained from global climate models. These data could also serve as a baseline for examining possible hydrological shifts resulting from climate change if a truly global measuring system were to be established (Rodenburg, 1991).

Global monitoring of water quality is the responsibility of GEMS, which is now the responsibility of the Environmental Assessment Programme of UNEP (see page 210). It promotes measurement of about fifty indices of quality, but practice varies considerably among the several hundred stations (in over forty countries) who participate. Monitoring of levels of agricultural and industrial pollutants, and of bacteria in surface and groundwater, is particularly relevant since changes in their concentrations may indicate changes in run-off patterns, and thus in climate (Kaczmarek et al., 1996).

Table 9.1. Examples of satellites used in the monitoring of global environmental change

Name	Origin	Status	Objective
ERS-1	Europe	in orbit	Data on ice patterns, land and sea surface temperatures
ERS-2	Europe	in orbit	Same as ERS-1 plus ozone-mapping and ozone-monitoring instruments
JERS-1	Japan	in orbit	Data on land, atmosphere and sea
Radarsat	Canada	in orbit	Measurements of Earth's surface
ADEOS	Japan	1996	To study the chemistry of troposphere and stratosphere, collect land and sea data
Meteor 3M-1	Russia	1998	To measure atmospheric aerosols and chemical species
ADEOS II	Japan	1999	Surface wind speed and direction over the global oceans
NOAA series	USA	continuous	Weather satellites; also gather data on global change
DMSP series	USA	continuous	Defence weather satellites; data on atmosphere and sea
Meteosat	Europe	continuous	Weather satellite, data on global change

Source: Lawler, 1995.

Increases in algal blooms in oceans, rivers and lakes, measured as chlorophyll a, could be used as another indicator of global warming. Formation of large floating masses of cyanobacteria or blue-green algae is now observed more frequently. Certain species can produce toxins; rashes, eye irritation, vomiting, diarrhoea and muscle pain have occurred in people who have swum through algal blooms. Blooms are considered to be caused in some areas by a combination of calm sunny periods and an over-abundance of nutrients, notably phosphorus (Elder, Hunter & Codd, 1993).

Food production and food security

As discussed in Chapter 5, agricultural production is strongly related to climate variables, particularly precipitation and temperature. Climate change can be expected to alter these. Additionally, extreme weather events, sea level rise and increased ultraviolet radiation (UVR) will impinge on agriculture. The potential impacts of climate change on food production and food security are therefore of some concern. Predicting these impacts, which will probably be subject to considerable geographical variation, is difficult though. Close monitoring is therefore essential, to provide early warning of shifts in growing seasons and in the geographical ranges of crops, and to improve predictive capacity.

Several systems have been developed by international agencies to provide early warning of food shortages. The most comprehensive of these is the Global Information and Early Warning System (GIEWS) of the Food and Agriculture Organization (FAO) of the United Nations. GIEWS maintains a close working relationship with the UN/FAO World Food Programme, various food aid donor agencies and the International Wheat Council. Its principal tasks are to collect and disseminate standardized information on food supply and demand conditions, to identify countries or regions where food shortages are imminent, and to assess possible emergency food requirements. Data obtained on the ground, pertaining to levels of basic food stocks and commodities (for example, wheat, rice, coarse grains, milk and milk products, oilseed, oils and fats, meats, sugar, cassava, pulses, livestock feed and fertilizers) and areas planted early in the season, are combined with satellite data on land use, vegetation cover and soil moisture, in order to predict fluctuations in food supply. Data on food prices in local markets are also collected since these reflect food availability. Anthropometric surveys or, in extreme cases, mortality rates, are also evaluated to help predict the impacts of food shortages on levels of nutrition and health. However, combining and aggregating the relevant data is sometimes difficult owing to the different methods used to collect data. Recommendations have therefore been made concerning standardization of these methods, particularly those used to carry out surveys of morbidity, mortality and nutritional status during emergencies (Boss et al., 1994).

Early warning services provided for countries by systems such as GIEWS are based on indicators extracted from the data collected. These indicators are broadly categorized into three kinds. *Leading* indicators are those that have low predictive power, but that could, in combination with other indicators and if used cautiously, provide early (ranging from several months to several years) warning of impending food insecurity. *Trailing* indicators, on the other hand, provide additional quantifiable parameters once a food emergency has arisen. As such, trailing indicators are particularly useful in monitoring progress towards recovery from food shortages. *Intermediate* indicators straddle the two groups and can either be used in combination with leading indicators to increase the predictive power of the latter, or with trailing indicators to assess the success of interventions. Examples are given in Box 9.9.

Box 9.9. Examples of indicators of famine used in early warning

The following is a selection of *leading*, *trailing* and *intermediate* indicators of famine as used by the Global Information and Early Warning System of the Food and Agriculture Organization of the United Nations with reference to early warning of food emergencies, or monitoring of progress of a country or region towards recovery from a famine.

Leading indicators	Low acreage under cultivation Drought Floods Low food reserve Political instability Population movement Strong black market Insect infestation (e.g. locusts)
Intermediate indicators	Crop failure Increased price of staple foods Rise in ratio of staple crop price to daily wage Increased lending rates Sale/consumption of livestock Death of livestock in pastoral societies Sale of valuable possessions (animals, jewellery) at less than market value Increased seed cost Seed shortage Consumption of seed grain Sale of land Population migration External market-price manipulation through subsidies, tariffs, etc.
Trailing indicators	Increased rates of low or abnormal anthropometric measurements Oedema/marasmus among young children Increased rates of vitamin deficiencies Increased rates of other nutritional deficiencies Increased mortality

Source: Toole & Foster, 1989.

As well as using data collected on the ground, GIEWS and other agencies incorporate suitably aggregated satellite data as real-time indicators of food supply and impending famine into their monitoring systems in order to improve consistency of information between countries and timeliness. "Greenness" indices, such as the Normalized Difference Vegetation Index (see Box 9.4), and rainfall assessments (based on the duration of cloud cover), for example, are compiled from data provided by satellites such as the Meteosat which covers Europe and northern Africa and NOAA satellites which cover Africa, the Middle East and south-west Asia. The data produced can also help to predict locust infestations.

Projects are also underway to increase understanding of the impacts of climatic and non-climatic factors upon agriculture. A project of the International Geosphere–Biosphere Programme (IGBP), for instance, consists of a global network that is modelling crop yield responses to environmental change, while another, conducted jointly with the International Council of Scientific Union's International Human Dimensions of Global Environmental Change Programme, will monitor long-term changes in global land use for agriculture that are driven by non-climatic influences such as population growth and trade agreements (IGBP, 1994) (see also page 211).

Agricultural pests and pathogens should also be monitored, since many of them — due to their mobility, high population growth rates and sensitivity to changes in climate — are likely to serve as early warning that climate change is occurring (see Box 9.5). Besides, since they also affect agricultural productivity, monitoring of the distribution of pests and plant diseases should be considered an important component of systems intended to monitor climate change impacts on food supplies. Climate change can also be expected to lead to an intensification of chemical control of pests, diseases and weeds. This could in turn cause an upsurge in resistance and higher levels of ecosystem pollution and food contamination. Monitoring of types and amount of chemical control should therefore be developed too.

Emerging and resurgent infectious diseases

The association of many infectious diseases with climate is demonstrated by their geographic distributions. As discussed in Chapter 4, climate change could particularly affect transmission rates of those vector-borne diseases and infectious diseases caused by pathogens with free-living life-cycle stages. Moreover, by causing alterations in ecosystem functioning and in the components of biodiversity, climate change could upset the ecological balance between parasites, intermediate hosts, vectors and humans, thereby creating new and unusual transmission cycles.

Evidence is accumulating that many emerging and resurgent infectious disease outbreaks observed in recent years have indeed been attributable to extreme weather conditions that have occurred in combination with or resulted in environmental change. Emerging infectious diseases are infections that are new in a population, rapidly increasing in incidence, or expanding in geographical range. Examples include dengue, hantavirus pulmonary syndrome, and some haemorrhagic fevers. Most emerging diseases are caused by changes in "microbial traffic" — that is, the introduction and dissemination of existing agents into human populations either from other species, or from other, smaller, human populations. This process is often precipitated by ecological or environmental change and facilitated by population movements and other social factors (see Box 4.4). Resurging diseases are those that were decreasing in incidence but that are now rapidly increasing in incidence. Commonly, the reason for this is that active control programmes for public health have been allowed to lapse. This has occurred in the case of malaria (*vis-à-vis* surveillance and vector control), diphtheria (*vis-à-vis* surveillance), and cholera (*vis-à-vis* quarantine) (CDC, 1994d).

The newly-established US-based Federation of American Scientists' Program for Monitoring Emerging Diseases (ProMED, sponsored by WHO) facilitates worldwide electronic data exchange on infectious diseases. Conceived as a computer-based network directly linking field scientists, it ensures that emerging infectious diseases are identified quickly. At the initiative of the Committee on Science, Environment, and Technology (CISET) of the interagency US National Science and Technology Committee, ProMED is also planning an international computer network to monitor

Table 9.2. Examples of potential members of a global monitoring and surveillance network for emerging and resurging diseases

Existing networks	• PAHO Polio Eradication Surveillance System • International Clinical Epidemiology Network • International Office of Epizootics Worldwide Information System • WHO Arbovirus and Haemorrhagic Fever Collaborating Centres • WHO Global Influenza Surveillance Network • CDC Field Epidemiology Training Programs
Existing research facilities	• Caribbean Epidemiology Centre, Trinidad. • CDC: National Center for Infectious Diseases Field Stations (Côte d'Ivoire, Guatemala, Puerto Rico, Kenya, Sierra Leone, Thailand). • DOD: US Army Research Facilities (Brazil, Kenya, Thailand) and US Naval Research Facilities (Egypt, Indonesia, Peru). • FAO Reference Centers (Argentina, Brazil, Colombia, Panama, Uruguay, USA, Czech Republic, France, Germany, Hungary, Spain, UK, Kenya, Senegal, Sri Lanka, Thailand). • French Scientific Research Institute (e.g. Congo, Côte d'Ivoire, Senegal). • Instituto de Nutriciòn para Centro America y Panama, Guatemala. • International Center for Diarrhoeal Disease Research, Bangladesh. • NIH: National Institute of Allergy and Infectious Diseases Supported Facilities (e.g. Brazil, Colombia, Mexico, Venezuela, Israel, Mali, Sudan, Uganda, Zimbabwe, Philippines). • Pasteur Institutes (e.g. Algeria, Central African Republic, French Guyana, Madagascar, Morocco, Senegal, Viet Nam, Iran).

Source: CDC, 1994d.

emerging infectious diseases. The network will include assessment of training and human resource needs. CISET is also planning to establish sentinel sites, including "critical geographical areas", that is, areas where life-support systems such as soil and water are severely stressed (Kasperson & Kasperson, 1995). This sentinel sites network, and the communications network provided by ProMED, should complement and provide mutual support for interlocking systems of environmental monitoring, such as GCOS, GOOS and GTOS (see pages 205–209).

Meanwhile the US Centers for Disease Control (CDC) and WHO are planning an international consortium of regional centres that will undertake enhanced surveillance of the emergence, resurgence and redistribution of infectious diseases, and identify the most appropriate clinical, laboratory and epidemiological responses.

Examples of the agencies or parties that could contribute to a global surveillance network for emerging and resurging diseases are given in Table 9.2. At this stage, these institutions are not under any obligation to take part in such services. Such a network could eventually be integrated with other systems that monitor the environmental impacts of climate change. In conventional epidemiological surveillance, recognition and reporting of only a small fraction of cases may be sufficient. But for emerging diseases, even a single unusual incident may be significant. (To be useful, monitoring must identify almost every single case of an emerging disease. This stringent requirement does not apply to routine disease surveillance.) Effective investigation of such incidents requires a structure that links clinical identification of a "new" syndrome or disease outbreak, to epidemiological investigation of the event (usually a weak aspect) and to laboratory analysis (to confirm diagnosis and characterization of the disease agent). Existing facilities, including some WHO collaborating centres for arboviruses and haemorrhagic fevers, could be a starting-point for such a monitoring structure.

It is significant that two Resolutions (WHA48.13 and WHA48.7) were adopted at the 48th World Health Assembly, held in Geneva in May 1995, urging WHO to assist countries in stepping up active surveillance activities aimed at the early detection of disease outbreaks and prompt identification of new, emerging and resurging infections, and to revise the *International health regulations*. These last are now too outdated to counter the steep increases worldwide in the mobility of people and goods, which do much to promote the spread of infections. Regrettably, neither of these resolutions refers to global climate change as a potential contributory factor to increased infectious disease incidence.

Vector-borne diseases

Vector-borne disease monitoring is important for four reasons (Rogers & Packer, 1993):

- to confirm the common-sense predictions made on the basis of data collected earlier (for example, concerning the relative importance of directly and indirectly transmitted diseases in urban vs. rural areas);
- to guard against overly simplistic extrapolation from the present to some future (incompletely specified but changed), possibly warmer, world;
- to demonstrate that we can identify and prepare for the likely impacts of climate change (for example, by determining the environmental constraints of important disease vectors, and by monitoring the impact on vector-borne diseases of climatic cycles, such as the El Niño/ Southern Oscillation);
- to contribute to the assessment of current vector control methods, and the development of new ones based on environmentally-sound principles.

Climate change may first affect vector-borne diseases at the margins of their current distributions. Thus as isotherms shift polewards, vector-borne disease may follow; for example, yellow fever outbreaks are more likely between the 10°C winter isotherms (Maurice, 1993). Monitoring should therefore be carried out at the margins of current distributions in order to detect changes. For example, in South America, Chagas disease could be monitored in Chile and Argentina, since the outer edges of the endemic area currently fall within these countries. Climate change may also affect the altitude at which vector-borne diseases are found. High altitude sites in Kenya, Rwanda, Argentina and Costa Rica have already experienced changes in vector-distribution and may be good sites for monitoring diseases such as malaria and dengue.

Low-cost continuous monitoring may be possible through local primary care facilities provided health staff are trained to diagnose malaria and other conditions, and to keep accurate records. In fact, this type of monitoring has already proved effective in Rwanda, enabling changes in temperature and rainfall to be linked to malaria incidence (Loevinsohn, 1994). Not only climatic changes, but also climatic events, such as ENSO episodes, have been linked to the incidence of some vector-borne diseases. Forecasting disease epidemics using climate data may therefore be possible.

Table 9.3. Summary of methods needed to monitor the health impacts of climate change and stratospheric ozone depletion

What	Where	How
Heat stress	Urban centres in developed and developing countries	Daily mortality and morbidity data
Changes in seasonal disease patterns (e.g. asthma and allergies)	"Sentinel populations" at different latitudes	Primary care morbidity data, hospital admissions, emergency room attendance
Natural disasters	All regions	Mortality, morbidity data (see main text)
Effects on health of sea level rise	Low-lying regions	Local population surveillance
Algal blooms, biotoxins, cholera	Marine (and freshwater) ecosystems	Local sampling, communicable disease surveillance centres, remote sensing
Freshwater supply	"Critical regions" especially in the interior of continents	Measures of run-off, irrigation patterns, pollutant concentrations
Food supply	Critical regions	Remote sensing, measures of crop yield, food access, nutrition (from local surveys). Agricultural pest and disease surveillance
Emerging diseases	Areas of population movement or ecological change	Identification of "new" syndrome/disease outbreak, population-based time series, laboratory characterization
Vector-borne diseases	Margins of distribution (latitude & altitude)	Primary care data, local field surveys, communicable disease surveillance centres, remote sensing
Skin cancers	High & low altitudes	Cancer registries, epidemiological survey
Cataract	As for skin cancers	Epidemiological survey

Source: Haines, Epstein & McMichael, 1993.

Climate change may result in the elimination of some vectors and/or pathogens — for instance, as a result of very hot dry conditions. Such conditions can also occur as a result of local activities such as deforestation (see Box 9.6 for an example) and therefore need to be distinguished from conditions arising from global climate change. Monitoring local ecological changes is nevertheless an important component of integrated assessment, as environmentally degraded areas are likely to be particularly vulnerable to climate change.

In view of the significant impacts that climate change could have on incidence of vector-borne diseases, existing standard infectious disease monitoring systems should be strengthened. This will require improvement of laboratory facilities, training of greater numbers of personnel, and fundraising. Data collection, standardization and coordination among centres should also be enhanced and an integrated database built, and linked to the ProMed and CISET initiatives. Such a database would enable disease outbreaks to be analysed with reference to data from other, socioeconomic, ecological and climatological databases. Moreover, since vector-borne disease incidence is influenced largely by the interaction of climate with vector abundance, human presence, economic activity and infrastructure, vector-borne monitoring must incorporate GIS-based monitoring. In many cases, identification of risk areas could be improved further by use of remote sensing data (see Box 9.4). Sentinel sites must also be incorporated into such monitoring (Thacker & Stroup, 1994).

Stratospheric ozone depletion

To assess the health impacts of enhanced UVR resulting from stratospheric ozone depletion, two trends must be monitored: global changes in column ozone abundance, and regional and global changes in ground-level UVR.

Ozone trends have been monitored using data from satellites, ground-based spectrometers, and ozonesondes (WMO/UNEP, 1992b; Gleason et al., 1993). Halocarbons, which are one of the major destroyers of stratospheric ozone, are measured in the troposphere by ships and aeroplanes. In the stratosphere, halocarbon levels are measured using *in situ* air sampling equipment aboard aeroplanes and balloons, and via infrared remote sensing devices attached to aeroplanes, balloons, and orbiting platforms. The data collected are used to predict future trends in ozone loss.

Serious international cooperation on monitoring of UV-B ground-level radiation has only just begun, although many governmental agencies are now acquiring the requisite and expensive instrumentation. Until recently, only broad-band measurements of UV-B were available, but the latest instruments provide spectral resolution so that UV-A and UV-C can now also be distinguished (see, for example, Kerr & McElroy, 1993).

The anticipated human health effects of stratospheric ozone depletion include increased incidence of skin cancers (basal cell, squamous cell, melanoma), cataract, and other possibly UV-B induced disorders of the eye (see Chapter 8). Incidence of each of these should therefore be monitored over a range of latitudes. But although data on melanoma can be captured via cancer registry data, basal cell and squamous cell cancers may be reported less reliably. Accurate estimates of cataract prevalence will probably necessitate periodic epidemiological surveys using a standard system to grade lens opacity (Chylack et al., 1993). However, since these potential clinically-defined end-points may take years to become manifest, earlier predictive markers should also be monitored. One option would be to use biological markers; for instance, certain mutations of the p53 gene in skin cells, which appear to be induced specifically by UV exposure (Nakazawa et al., 1994). Skin cells from some animal species that live at high latitudes, where ozone depletion is greatest, might also be monitored.

Current global monitoring framework

More than 80 international institutions and programmes are involved in global environmental monitoring, data management and coordination (Rodenburg, 1991). A short overview of the major climate and environment monitoring efforts undertaken on behalf of or by the UN system is provided in this section. Unfortunately, human health issues are still poorly represented in most of the monitoring systems described here.

Table 9.4. International agencies addressing aspects of climate change. Some of the on-going activities and responsibilities of each agency are shown.

ICSU (International Council of Scientific Unions)	• WCRP (World Climate Research Programme)* • IGBP (International Geosphere–Biosphere Project) • IHDP (International Human Dimensions of Global Environmental Change Programme) • GCOS (Global Climate Observing System) • GTOS (Global Terrestrial Observing System)
UNDP (United Nations Development Programme)	• GEF (Global Environment Facility)
UNEP (United Nations Environment Programme)	• IPCC (Intergovernmental Panel on Climate Change) • World Climate Impact Assessment and Response Strategies Programme* • GCOS • GTOS • Montreal Protocol • GEF
UNESCO (United Nations Educational, Scientific and Cultural Organization)	• IHP (International Hydrological Programme) • IOC (Intergovernmental Oceanographic Commission) • GLOSS (Global Sea Level Observing System) of IOC • GTOS
WHO (World Health Organization)	• WHO/WMO/UNEP Task Group on Health Impacts Assessment of Climate Change • EMC (Division of Emerging and other Communicable Diseases Surveillance and Control)
WMO (World Meteorological Organization)	• IPCC • WCRP* • World Climate Data and Monitoring Programme* • World Climate Applications and Services Programme* • GCOS • GTOS • WWW (World Weather Watch) • HWR (Hydrology and Water Resource Programme) • GAW (Global Atmosphere Watch)

* component of the World Climate Programme (WCP)

Global climate monitoring is required so that measures for mitigating climate change may be agreed upon internationally on the basis of a sound understanding of climate variability and change. The Second Climate Conference, held in Geneva in 1990, recognized this need and the Global Climate Observing System (GCOS) was subsequently established as a joint initiative of WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, UNEP and ICSU (GCOS, 1995). Intended to be a long-term, worldwide, user-driven operational observing system, GCOS has been designed specifically to meet comprehensive scientific requirements for monitoring climate, and to provide the observational basis for predicting climate variations and change, detecting climate change and recording its impacts. It will address the total climate system and cover a wide range of interdisciplinary topics that deal with physical, chemical and biological properties and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. It is a key element in support of WMO's World Climate Programme, which incorporates climate research, data and monitoring, applications and services, and impacts and responses.

More particularly, GCOS will provide national governments with the information, previously lacking, that will enable them to answer the critical scientific, economic and policy questions arising in connection with the impacts of climate change on their countries. Systematic and comprehensive global observations of the key variables, for instance, are urgently needed so that governments can:

- detect and quantify climate change at the earliest possible time;
- document natural climate variability and extreme weather events;
- model, understand and predict climate variability and change;
- assess the potential impact of climate change on ecosystems and socioeconomic systems;
- develop strategies for diminishing potentially harmful effects;
- support sustainable development.

GCOS will not itself undertake climate observations or generate data products, but will rather encourage, coordinate and otherwise facilitate observations that must be made by national or international organizations in support of their own requirements and common goals. GCOS will, however, provide an operational framework for integrating the observational components of the participating countries into a comprehensive system. In this way, a coherent observational capability can be established, based on existing national and international operational and research programmes. When observations or data management structures that are required are unavailable, efforts to initiate them will be undertaken through GCOS.

GCOS coverage exceeds that of current monitoring programmes such as Global Atmosphere Watch (GAW), and the World Weather Watch (WWW) network of satellites, telecommunication, and data processing facilities (see Fig. 9.3). Much of what is currently known about variations in Earth's climate system has been gathered from data collected for other purposes, such as weather forecasting. However, this information is often incomplete and not sufficiently accurate for elucidating climate change. For example, upper air measurements taken for World Weather Watch are mainly concentrated over land; few data about rainfall or evaporation over oceans are available. Gaps such as these should be filled so that a truly comprehensive climate observation system can be established.

GCOS will take advantage of on-going and proposed satellite missions and the activities of the World Climate Research Programme which was created to determine how human activities are affecting the climate system. (Table 9.4 shows some of the international organizations currently involved in addressing climate change.)

The Global Ocean Observing System (GOOS) and the Global Terrestrial Observing System (GTOS) are also contributing to observation of global climate. GOOS is being developed mainly by the IOC of UNESCO. One of this system's modules will be devoted specifically to climate, and will incorporate GLOSS. (GLOSS is operated by the IOC of UNESCO, and as such forms part of that organization's contribution to GOOS.) GOOS will improve the quality of ocean measurements, many of which are currently not recorded on adequate temporal and spatial scales, and measurements for some geographical areas, including the southern latitudes and polar regions, which are currently not well covered. It will also develop cloud radiation monitoring, and methods for observing land characteristics (including type of land cover, vegetation structure and function) and the hydrological cycle.

Fig. 9.3. Global observing systems

	ATMOSPHERE		LAND	OCEANS
	WWW	**GAW**	**GTOS**	**GOOS**
GCOS		climate	climate	climate
	weather	air pollution ozone	land degradation pollution biodiversity anthropogenic impacts on natural systems	marine services coastal zone management ocean ecosystems living marine resources

GOOS will use a range of monitoring methods including remote sensing, observation from ships, and use of a range of buoys, autonomous motor vehicles, and fixed or moored instruments on the sea bed or in mid-water. The system will be implemented in stages. Thus some variables such as global surface temperature will be monitored over a large area before less directly measurable parameters, such as phytoplankton concentration, are monitored. Studies of the overall costs and benefits of GOOS have been undertaken, both internationally and on a country basis. In countries around the Arctic Ocean, the information of most value is that on sea ice movement and how this influences weather.

The Global Terrestrial Observing System (GTOS) is being established under the auspices of UNEP, UNESCO, FAO, WMO and ICSU. It will be used to calibrate and validate ecosystem models, to detect and monitor the responses of terrestrial ecosystems to global change, and to observe changes in agro-ecosystems caused by new patterns of land use (IGBP, 1993). GTOS will be providing the terrestrial component for global climate monitoring (Fig. 9.3).

GTOS will need to include a wide range of socioeconomic variables since socioeconomic factors are major driving forces for terrestrial ecosystem changes. Additionally, it must be designed to meet the practical needs of national planners, particularly those in developing countries who require better data on land use, and the research needs of the international scientific community. Specifically, GTOS must:

- Be global in scope, meaning both that its coverage is comprehensive (but regionally balanced and resolved) and that it addresses phenomena that are global in their nature or impact.
- Provide continuity of information collection over the long-term — periods from years to decades which are consistent with the rate at which global processes occur — in order to detect trends sensitively and in a timely fashion.
- Represent an integrated system in which the separate pieces of information add to each other's value. For example, GTOS data must not only detect and describe changes, but enable them to be understood and predicted.

The mechanism proposed for GTOS is a four-level hierarchical system based on existing sites and networks and on present and planned remote sensing systems. At level four it is proposed to measure a limited range of relatively simple variables, such as soil carbon, which can be standardized easily. These variables will be monitored every five and ten years at 10 000 sites of approximately one hectare in extent. These small sites will need to be selected, dedicated and the necessary instruments installed. Level three sites will include many existing national agricultural research stations and ecological monitoring sites. Around 1000 sites will be selected to represent the world's major biomes, agro-ecological regions and farming systems. The focus of level two sites will be similar but a greater range of variables will be measured with greater frequency. The 100 level two sites will be based largely at existing major research centres. Level one sites will number between 10 and 20 sites only, and will be sites that already form part of international experiments; for instance, sites included in IGBP. They will be used to monitor changes in important large-scale processes such as soil transport and movement of biota.

IGBP is another global monitoring programme and seeks to "describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in the system, and the manner in which they are influenced by human activities" (IGBP, 1992). A number of IGBP core projects have a strong emphasis on monitoring. Data collected by IGBP projects are used for the development, calibration and validation of models. In particular the Global Change in Terrestrial Ecosystems project is attempting to predict the effect of changes in climate, atmospheric composition and land use on terrestrial ecosystems, including agricultural and forest systems, and to determine how these feed back into the atmosphere and climate system. It is also taking the lead in the development of GTOS. Another IGBP programme, START (global change SysTem for Analysis, Research and Training) aims to establish regional research networks for all the world's major biomes and depends on other systems, such as GCOS and GTOS, for sources of information (IGBP, 1994).

Role of WHO and other UN agencies

The specialized agencies of the United Nations are primarily mandated to support government planning and management in Member States, by strengthening sectors such as industry, health and agriculture. This is typically achieved through capacity-building and provision of expertise, information and other resources. These agencies also play an important role in assisting countries to apply internationally-agreed rules and regulations, and quality standards. Accordingly, these agencies consider that global environmental and health monitoring systems should principally serve the needs of Member States regarding selection and implementation of mitigative and adaptive measures pertaining to the impacts of global climate change.

WHO, in collaboration with other international agencies, assists its Member States with implementation of environmental health monitoring systems. The focus is on supporting research activities, standard-setting, data exchange and training in health risk assessment and environmental epidemiology. But greater emphasis must now be given to helping countries where there is a particular need to improve vulnerability assessment, to identify climate change health risks, and to define data needs and data resources for mitigation and adaptation programmes.

The strengthening of intersectoral efforts (for example, between the health, meteorology, agriculture, and fisheries sectors) to assess and monitor relevant climate change and environmental change indicators should be a longer-term goal. Linkages between health-related early warning systems already in existence, such as GIEWS (see page 199), and ProMED (see page 201), should also be strengthened, especially at field level.

WHO already collaborates with other UN agencies on a number of monitoring programmes. Within GEMS (see page 179), WHO and UNEP produce guideline documentation on various issues related to the monitoring and assessment of air and water quality and pollution, on dietary intake of contaminants, and on the genetic effects of environmental hazards. Certain GEMS components focus on specific environmental compartments or sources of human exposure (i.e. water, food and air). With additional resources, such systems could be extended to include exposures to the direct and indirect hazards associated with climate change, such as increased UVR and sea level rise.

Since its inception in 1972, UNEP has concentrated on monitoring, assessment and management of the impacts of environmental degradation on human health and the natural environment. For example, since 1982, together with WHO and FAO, UNEP has been promoting the safe use of pesticides and environmental management as an alternative to the exclusive reliance on chemicals for pest and vector control. Likewise UNEP and WHO jointly review the impact of marine pollution on human health and have issued guidelines for monitoring and controlling the pollution of coastal waters. This collaboration could be extended to include the effects of algal blooms and of fish and shellfish poisoning. Indeed a widening of the mandate of the Joint Group of Experts on the Scientific Aspects of Marine Pollution, sponsored by WHO, UNEP and other UN agencies, should be envisaged so as to include more health-related aspects of climate-induced oceanic changes. A collaborative agreement between GCOS, GTOS, and GOOS (see pages 205–209) would be needed to identify sensitive areas and to link health and pollution databases with the collection of climate data.

In view of growing demands for development-oriented environmental information following the adoption of *Agenda 21* at the United Nations Conference on Environment and Development in 1992, UNEP has recently restructured and integrated its monitoring, assessment and reporting functions. The new Environment Assessment Programme now incorporates GEMS, the Global Resource Information Database, and the UNEP units responsible for reporting for the State of the Environment programme and coordination of the UN-system-wide Earthwatch Programme (UNEP, 1994c). The new programme has a number of objectives including:

- provision of an information base for policy formulation and raising of environmental awareness;
- support for the production not only of sectoral information but also of integrated environmental information for sustainable development;
- provision of data and scientific assessments of environment and development linkages for a wide range of users;
- emphasis on emerging issues and early warning, in addition to description of the present situation;
- creation of an integrated UNEP information delivery system rather than a set of disparate systems.

At an administrative level, UNEP provides the secretariat for the Montreal Protocol on Substances that Deplete the Ozone Layer (see Box 2.4) and for the Basle Convention on Transboundary Movement of Hazardous Wastes.

Since many UN agency activities overlap, a framework aimed at integrating international climate-related programmes was adopted at the WMO Congress of June 1995. Entitled *The climate agenda*, it proposes inter-agency collaboration on climate issues in four main areas:

- new frontiers in climate science and prediction;
- climate (rather than weather) prediction services for sustainable development;
- studies of climate impact assessments and of response strategies for reducing vulnerability;
- observation of the climate system.

The climate agenda is expected to assist international agencies in aligning their climate-related activities, in identifying priorities and resource requirements, and in acquiring resources. Hopefully, it will also serve as a mechanism for the periodic evaluation of progress towards international goals. Fulfilment of these functions should ultimately benefit individual countries, particularly concerning establishment or strengthening of national climate programmes, and in creating relevant scientific and technical capacity.

Role of the social sciences

Adequate consideration of the social and economic impact of climate change on human society, and of societal efforts to mitigate or adapt to such change, necessitates multidisciplinary research that draws heavily on the social sciences, particularly sociology, anthropology, social psychology, political science and economics. Only by undertaking such research will we able evaluate fully the effectiveness, efficiency and fairness of society's proposed responses to the impacts of climate change. Two important bodies have adopted just this approach.

The International Human Dimensions of Global Environmental Change Programme (IHDP), co-sponsored by the International Social Science Council and the International Council of Scientific Unions, is a prominent international multi-disciplinary scientific activity that draws heavily on the social sciences in relation to climate change impact analyses (see also page 201). Topics covered by the IHDP research framework include: the social dimensions of resource use; perception and assessment of global environmental conditions and change; environmental impacts caused by the policies of local, national, and international social, economic, and political structures and institutions; land use; and environmental security and sustainable development. Similarly, IPCC has relied extensively on the ideas and analyses of economists and other social scientists in its evaluations of the projected impacts of climate change and possible responses to them.

Role of economics

Economics is about the rational and efficient allocation of "scarce" resources (i.e. goods and services). It focuses on prompt return on investment and low-cost satisfaction of consumer demand, in order to meet the short-term priorities of the marketplace. The priorities of environmental policy-makers, on the other hand, include controlled use, avoidance of pollution and resource depletion, and maintenance of biodiversity, with the ultimate goal of ensuring the long-term sustainability of complex ecological systems. Much of the current disagreement between some economists and environmental policy-makers concerns how market-based valuation is reached.

Modern economics has evolved, over the past two centuries, as a liberalizing social device in Western society. The pioneering British economist, Adam Smith, envisaged a non-discriminatory market in which people participated on equal terms and bought and sold according to availability and need. Indeed, it has long been argued that Smith's much-quoted "invisible hand" of the marketplace should ensure a rational balance between supply and demand. Evidently, though, this ideal balance can occur only if participation in the market is free of social, political and commercial distortions.

Conventional economic theory is thus grounded in the interplay of supply and demand within the marketplace. If wider environmental considerations are not taken heed of, and there is accordingly no need to regulate markets, and if inequalities in wealth are tolerated, then market-based economics may indeed achieve efficient exchange of materials, commodities, labour and ideas. But in reality, "market failures" occur because most societies concern themselves at least to some extent with fairness, aesthetic considerations, and ecological sustainability and because market-based economies tend to:

- maximize the profitability of transactions, without regard to social equity;
- "externalize" the adverse impacts upon people or environment of economic activity, as in the case of the impaired health of factory workers or reduced air quality; such costs, borne in these instances by the workers, or by all organisms that depend on or breathe air, are not accounted for in the conventional market price;
- discount the future; discounting reflects the manifest "time preference" of human society (e.g. a dollar today is valued more than two dollars that would be acquired in a decade), and presents a particular dilemma when foreseeable costs and benefits will not occur until well into the future, since these distant outcomes are assigned negligible or zero value in today's market.

If market economies are not regulated adequately by government, and if levels of extraction, processing and consumption increase continuously, serious environmental degradation can occur. Evidence to this effect exists, at some level, in all developed countries — and more dramatically in some of today's rapidly industrializing countries, including Brazil, Mexico and the Republic of Korea. However, it is not the "freeness" *per se* of the market that causes the problem. Rather, it is the tendency of economic transactions in all human societies to ignore or discount material, social and environmental costs. If free-market processes and increasing levels of consumption were to become the norm worldwide, many more of the world's natural systems would become even more endangered. This would include the climate system. For example, if our priority is to maximize access to energy for industry, transport and domestic use via the quickest and cheapest means, fossil fuels will be burnt if available. Likewise, if a premium is placed on creation of new crop-land or pasture-land, especially in settings where adjoining fertile land has been allowed to degrade, forest clearance will continue. Both these economic activities generate vast amounts of CO_2.

In response to this apparent tension between conventional economics and environmental needs, some economists have developed an "environmental economics" (Daly & Cobb, 1989; Pearce et al., 1991; Arrow et al., 1995; Ekins, 1995). This is a body of economic ideas and theory that, in particular, seeks to include the otherwise externalized costs within market prices. It embraces the notion of sustainability (i.e. valuing the present and the future equally) and the need to protect the "commons" (i.e. assigning value to clean air, stratospheric ozone, forests, etc.). This approach seeks both to manage the budget of the *oikos* (home) — i.e. economics — and to manage the structural integrity and productivity of that *oikos* — i.e. ecology.

Internalizing the externalities, otherwise known as "full cost accounting", so that market values reflect the true aggregate costs to society and environment, both present and future, is a very important concept. For example, the price paid by the consumer for petrol would then take account of the estimated environmental costs of its production, transport and combustion; a carbon tax could also be included in the final price. Similarly, the fully-accounted cost of a logged tree would include the costs of estimated environmental damage, of lost income from tourism, and of longer-term impacts on ecological systems and biodiversity.

Some economists argue that if the calculus of the market-place is extended to encompass full-cost accounting, market mechanisms can continue to be considered a guide to rational transactions. But other economists argue that many indirect costs, especially those displaced onto the distant future, such as the gradual extinction of valued species, or the long-term accumulation of radioactive waste, cannot be sensibly dealt with in the marketplace (Ekins, 1995). They believe that instead society will have to develop extra-economic policies and procedures that deal with such items according to a different, qualitative set of criteria. This seems reasonable given that assigning money values to the various elements of the eco-sustainability equation is highly problematic. How, for example, in the light of its possible extinction due to changes in habitat boundaries following climate change, would we undertake the valuation of a particular species? The value (to us) of a species has at least three dimensions: its current usefulness to humans, its potential future usefulness (e.g. if its genes or its products are required by human society in future), and its existence value (i.e. the value we place on its "being"). Calculating such a composite valuation is clearly no easy task.

Placing a precise value on a human life is equally difficult. Economists have suggested various approaches:

- the prescriptive approach (what should a life be worth?);
- the descriptive approach (what value do our actions or policies actually put on a life?);
- the contingent approach (the willingness to pay for sustaining a life or willingness to accept monetary compensation in lieu of a specified, e.g. occupational, risk of death);
- the "human capital" approach (what is the economic productivity of the average person in society?).

But once again, complex and controversial issues abound. Resolution of at least some of these issues may now be occurring with the formulation and broad acceptance of an "ecological economics" (Jansson et al, 1994; Ekins, 1995). This form of economic thinking and analysis is even more accommodating of such difficult issues, recognizing the need for non-economic judgements as part of the substrate of decision-making. That is, it does not seek to constrain the primary social decision-making within the cost–benefit framework that has been progressively widely applied, to neo-classical economics, resource economics, and finally environmental economics.

Chapter 10

Recommendations and conclusions

Overview of a complex problem

Climates vary naturally around the world, and "the weather" is with us on a daily basis. Despite our knowledge of human physiological response to weather variables such as temperature and humidity, relatively little research has been directed at studying the actual health consequences of climatic variations. However, the prospect of long-term changes in the world's climate is now focusing new attention on this research area.

The population health impacts of global climate change could be wide-ranging. Moreover, since climate change is likely to disturb various natural and ecological systems, it is anticipated that most of these health impacts would be adverse. Some beneficial health effects would occur in some locations. It must be emphasized, though, that the forecasting of health impacts is necessarily contingent on assessments of the probabilities and anticipated consequences of climate change made by scientists working in other disciplines. Therefore, neither certain nor precise forecasts of health impacts can be made. However, this does not diminish the importance of devoting more resources to this topic, or of the need to implement measures to reduce both the rate of climate change and the vulnerability of poorly protected populations.

The scientific assessment of global climate change made by the Intergovernmental Panel on Climate Change (IPCC) foresees a rise in global mean temperature of 1–3.5°C over the coming century, accompanied by changes in the world's hydrological cycle (see Chapter 2). These forecasts of climate change and sea level rise form the basis upon which the climate change health impact assessments in this monograph have been made. Similarly, the scientific assessments coordinated by UNEP have provided the basis for considering the potential health consequences of stratospheric ozone depletion.

Most of our current environmental health problems occur on a local or regional level. However, many of the anticipated health effects of climate change would affect large populations in many regions. Additionally, many of these climate-related "exposures" would act indirectly, often via processes that are not yet well understood. Many health impacts would arise via disturbances of complex biotic and other natural systems, reflecting the fundamental link between the integrity of natural ecosystems and the long-term health of human populations.

In this context, it is important to note that ecosystems are subjected to many environmental stress factors, many of them the result of human activities or population pressure. Such factors could modify significantly the population health impact of climate change. For example, the responses of essential food crops to a change in climate will depend much on other ecological determinants, such as soil erosion, salt-water intrusion or salinization, the balance between pests and predators, and increases in ultraviolet radiation (UVR) levels. It should be borne in mind too that human populations and communities vary markedly in their vulnerability to climatic change and in the resources available to them for protection and mitigation. Many of the anticipated impacts would be greatest among the world's poor and disadvantaged populations.

For all these reasons, the assessment of potential health impacts requires the integration of information about climatic factors, ecosystem vulnerability, biophysical systems, and social-economic-political resources and responses.

Summary of anticipated health impacts of climate change

The anticipated health impacts of global climate change are categorized in Chapter 1 as either direct or indirect (see Fig. 1.1). But in reality they constitute a continuum rather than a simple dichotomy. The most direct health impacts would be those caused by heat waves, storms and floods; the least direct those due to socioeconomic disruption caused by environmental deterioration. Many health impacts would occur slowly, via climatic impacts upon agroecosystems, ocean fisheries and infectious disease transmission dynamics. If sustained climate change were to occur, these latter indirect impacts could well become the most significant.

Some of the health impacts occurring as a direct consequence of climate change would consist of increased incidence of familiar, existing public health problems. For example, an increase in the frequency or severity of heat waves would cause increases in heat-related mortality and illness. Studies in North America, North Africa and China indicate that in very large cities this would represent several thousand extra deaths annually. The extent to which increases in the numbers of heat-related deaths would be offset by a reduction in the numbers of cold-related deaths is unresolved; almost certainly the balance would vary by location and would also depend on adaptive responses. Climate change is also likely to bring about major regional shifts in precipitation patterns and, with them, increased frequency or severity of droughts, floods, and bushfires. Injuries, deaths, and psychological and social disturbances attributable to these causes would therefore probably increase in affected regions.

Climate change would tend to increase the geographic distribution (altitude and latitude) of disease vector organisms and to result in alterations to the life-cycle dynamics and seasonal activity of vectors and parasites. These effects would amplify the potential transmission of many vector-borne diseases. Some basic integrated mathematical models, based on knowledge of the climatic–environmental determinants of vector-borne diseases, predict potential increases in incidence of specific diseases under certain climate change scenarios. For example, an aggregated global model estimates that the proportion of the world population exposed to the *potential* transmission of malaria, in response to GCM climate change scenarios, will have increased from the current 45% to around 60% by 2100. Much of this increase would affect populations currently at the margins of endemically-infected areas, in tropical, subtropical, and some less well-protected temperate-zone regions. Increases in incidence of non-vector-borne infectious diseases, such as cholera, and other food-related and water-related infections, could also occur, particularly in tropical and subtropical regions, following climatic impacts on water distribution, temperature and the proliferation of microorganisms.

Climate change, via effects on soil, photosynthesis, pests and diseases, would affect agricultural productivity. Almost certainly, important regional differences would occur, with negative effects seen principally in lower-latitude lower-income countries. In regions affected negatively, malnutrition, hunger and health impairments could increase, particularly in children.

The production of some types of air pollutant and accordingly incidence of their associated health impacts, such as cardiorespiratory disorders, would probably be exacerbated by climate change. A warmer and wetter climate in some regions could also result in higher airborne concentrations of various pollens and spores with likely impacts on allergic disorders, such as hay fever and possibly asthma. Other indirect effects on health would result from the social-demographic disruptions caused by rising sea level and from those caused by climate-related regional shortages of fresh water, food and other natural resource supplies.

Sustained depletion of stratospheric ozone, resulting in increased ground-level UV exposure, would cause an increase in the incidence of skin cancer. It may also increase the incidence of ocular lesions (for example certain cataracts), as well as suppression of the immune system. Increased UVR would also impair, to some extent, the photosynthetic productivity of land plants and marine phytoplankton, both of which are basic sources of human food.

In view of this wide range of potential health impacts, the need for an expanded research effort, and for improved and international monitoring of health-risk indicators in relation to climate change and other associated global and regional environmental stresses, is obvious. Existing UN-system and other intergovernmental global monitoring activities should incorporate in their programmes health-related environmental and biological indicator measurements (including indices of insect, rodent and algal populations) and, where appropriate, direct measures of human population health status.

Recommendations

Earlier chapters have indicated that the health sciences must develop new and better methods for studying the relationship of population health to natural climate variability, and to human-induced climate change. This will assist public understanding of the nature of the climate change problem and its health consequences, and, therefore, the development of policy responses. We must become familiar with the scale and complexity of the problem, its inherent uncertainties, and the attendant need for precautionary inferences and policies.

Initiatives should be taken in the following four areas:

- Support for research institutions to undertake multidisciplinary projects assessing the potential health impacts of climate change, with special attention paid to current gaps in knowledge, using new and conventional research methods.
- Establishment of appropriate, globally-coordinated monitoring of changes in population health. This would facilitate early preventive interventions in vulnerable areas, and increase our understanding of the nature and magnitude of the health impacts of climate change and their interactions with local environmental change.
- Preventive (precautionary) approaches to reduce the pace and magnitude of climate change, in light of the possible irreversibility of some of the ensuing environmental/ecological changes and the range of potential adverse health effects that may result from them.
- Development of adaptive responses, particularly those that would have immediate benefits for health (no regrets principle).

These four areas are considered below in more detail.

Support for new and multidisciplinary forms of research

Interdisciplinary collaboration and the development of innovative scientific assessment methods should be encouraged to achieve greater integration between the human dimensions (i.e. social and behavioural sciences) and the geobiophysical dimensions (i.e. climatology, physics, biology and medicine) of this issue. This will require:

- A greater awareness among the public health research community and research funders and policy-makers of the anticipated long-term health outcomes of climate and ecosystem change.
- Incentives within research institutions to promote multidisciplinary collaboration. This will include overcoming barriers to interdisciplinary research, such as the vertical organization of research funding bodies, which leads to single-discipline funding, and the marked differences between disciplines in methods and technical language (CGCP, 1995).
- Improved communication between scientific disciplines, between scientists and policy-makers, and between the research communities of different countries and geographic regions.
- Creation of multidisciplinary scientific advisory boards able to address large-scale and long-term environmental and health issues. Government funding of key international organizations with the capacity to coordinate cross-sectoral global research initiatives should be increased.
- Improved orientation and strengthening of the role of international agencies (particularly WHO, WMO, UNEP and FAO) in providing technical support and policy advice to Member States regarding the human health implications of environmental change.
- Expansion and creation of electronic data management and exchange systems to address health–environment relationships. Electronic networking through the Internet should be expanded rapidly to include researchers in the developing world.

Proposed research areas

The inherent "newness" of this topic — climate change as a hazard to human health — means that there are many research needs. Much remains to be learnt, for instance, about patterns of health response to natural climatic fluctuations, about the ways in which complex ecosystems respond to shifts in mean seasonal and annual climate conditions and climate variability, and about techniques for developing and evaluating integrated predictive models.

Since many of the population health impacts of climate change would result from perturbations of natural biogeochemical systems, their scientific assessment will require a systems-based analysis appropriate to the study of complex systems and processes. (See, for example, the discussion of ecologically-based health risk assessment in Chapter 9). Scenario-based mathematical modelling techniques, if applied to simulating the dynamics of ecological systems, could assist in forecasting the likely human health impacts.

Major research needs include:

- Achievement of higher resolution in mathematical models for predicting the health impacts of climate change, to enable local and regional impact assessments to be made.
- Further studies to: (i) distinguish more clearly between the effects on health of climate and the effects on health of air pollution; (ii) determine the extent to which in different regions a reduction in cold-related mortality may offset the impact of more frequent heat waves, and (iii) assess the longer-term health effects, if any, upon populations living in locations with different average climates.

- Analysis of infectious disease epidemics associated with recent regional climatic changes, using these as analogues of future climate change. For example, a systematic examination of vector-borne disease outbreaks in regions affected by climate events related to the El Niño/ Southern Oscillation would improve our understanding of climate–health relationships.
- For vector-borne diseases: (i) basic laboratory and field investigations of arthropod vector ecology and pathogen infectiousness at elevated temperatures and varying humidity, and (ii) ecological studies on the climate sensitivity of diseases in locations at the margins (either by latitude or altitude) of endemic areas.
- Assessment of how alterations in food production as a result of climate and weather changes, increased UVR, sea level rise, changes in pest ecology, and socioeconomic shifts in land-use practices, could affect human health and nutrition.
- Population-based studies of trends in UV-B exposure using improved exposure-recording devices, and, where possible, incorporating biological indicators of early effects of exposure (for example, on skin or eye tissue).
- Modelling studies of the potential public health implications of forced migration from climatically vulnerable regions.
- Ecological studies of the range of possible public health impacts of climate-related declines in biodiversity.
- Assessment of the potential health impacts of strategies to mitigate greenhouse gas emissions (for example, the health risks of biofuels and biomass fuels, and the increased risk of schistosomiasis due to construction of dams).

Monitoring of health risks and health status

Existing global and integrated environmental monitoring systems collect little information explicitly related to health impacts, and indeed, are not well-adapted for the collection of such information. They therefore cannot undertake quantitative analysis of the gradual and long-term population health consequences of climate change. An effective system of longitudinal data collection is needed, however, since such a system would not only contribute to improving early warning systems but would also help to gauge the *magnitude* of impacts and guide the allocation of limited resources. Furthermore, if monitoring incorporated appropriate key biological indicators, it would yield information on the health risks associated with climate change sooner. Monitoring would then both contribute to improving understanding of the impacts of climate change and facilitate rapid response to them.

The cost–effectiveness of climate change monitoring systems must be considered. If this cannot be assessed prospectively, indicators which will be of local use, irrespective of the degree to which climate change occurs, should be favoured. An example would be monitoring changes in the incidence of major vector-borne diseases. Some of the relevant criteria in selecting indicators are:

- the size of the population at risk;
- the sensitivity of this population to the different potential impacts of climate change;
- the potential to build on existing monitoring systems or longitudinal databases;
- the infrastructure available for new monitoring initiatives.

If a global health monitoring network is established, cooperation between developed and developing countries will obviously be essential. For instance, collaboration between technically advanced countries implementing remote satellite imaging and poorer countries with valuable field data from relatively sensitive or vulnerable geographic locations, will prove more effective than disjointed efforts at national level.

Monitoring initiatives could include:

- Determining key health indicators to be incorporated within an expanded Global Climate Observing System, and especially within the Global Ocean and Terrestrial Observing Systems.
- Introducing relevant health indices into the International Human Dimensions of Environmental Change Programme of ISSC and ICSU, and UNESCO's Man and Biosphere Programme.
- Monitoring mortality and morbidity trends following heat waves, in selected sentinel cities.
- Monitoring the incidence of vector-borne diseases and movement of vectors at the margins of their current distribution. (Shifts in the altitude and latitude of distribution can signal new trends.)
- Monitoring changes in the seasonal incidence of specific illnesses, such as asthma, and foodborne and waterborne infectious diseases.
- Global monitoring of terrestrial and marine food production, with particular attention paid to regional variations.
- Monitoring of food supply and nutritional status of sentinel populations, including the use of anthropometric indices (preferably under the leadership of the Food and Agriculture Organization (FAO) and WHO).
- Monitoring of marine ecosystems and particularly of algal blooms and toxic phytoplankton species.
- Monitoring for UV-induced DNA damage in superficial tissues of indicator species (many of which live at high latitudes, and are subject to declining UV protection because of stratospheric ozone depletion).
- Monitoring the rate of enforced human migration from regions judged to be the most vulnerable to environmental disruption caused by climate change and to the impact of extreme weather events.

These and other monitoring options would complement existing environmental monitoring systems, such as the Global Environment Monitoring System of WHO and UNEP, and FAO's Global Information and Early Warning System. This type of coordinated programme could promote the integration of data collection from around the world and, in view of the likely interplay between the effects of climate change and other environmental stresses, should be encouraged. Improved electronic information systems will be needed, however, if scientists are to make best use of incoming data (see Box 10.1).

Development of preventive strategies

Preventive strategies in public health are conventionally classified as either primary, secondary, or tertiary. Primary prevention refers to avoidance or removal of a hazardous exposure or other circumstance. Secondary prevention, which is more "downstream" than primary prevention, involves the early detection of a subclinical health disorder and subsequent intervention to avert progression to overt disease. Tertiary prevention, via treatment, attempts to minimize the adverse effects of disease. In general, the further "upstream" the intervention, the greater the number of people that will benefit.

Box 10.1. Networking information systems

Many resources are available that can assist researchers, policy-makers, and academics in locating information on the health impacts of climate change. However, although the number of databases containing information on the physical science of global climate change is large and growing, those containing health-specific information are fewer. WHO therefore initiated the setting up of a database, CLIMEDAT, to improve networking between researchers and organizations working on the health aspects of climate change.

At a more general level, the Consortium for International Earth Science Information Network (CIESIN), established in 1989 as a private, non-profit organization, is promoting the interdisciplinary study of global environmental change. Its efforts are directed toward the exchange of data generated or collected by the US Government, international governmental organizations, policy-makers, and academics. For example, CIESIN now disseminates the WHO Mortality Database. CIESIN also supports:

- the Socioeconomic Data and Applications Center of the NASA Earth Observing System Data and Information System;
- the US Global Change Research Information Office, which is mandated by US Congress;
- the International Human Dimensions of Global Environmental Change Programme Data and Information System, which operates under the auspices of the International Council of Scientific Unions and the International Social Science Council;
- the International Secretariat of the System for Analysis, Research, and Training, which is a programme of the International Geosphere–Biosphere Programme;
- the World Climate Research Programme.

Electronic telecommunication is becoming invaluable, especially for international coordination and data retrieval. For Internet access, recommended systems to go through include World Wide Web and Gopher. Resources for on-line searching are becoming increasingly extensive; the UN's Infoterra, for example, compiles environmental information covering 99% of the world's population and provides librarian assistance to access these databases. Information about many health and health-related statistical databases, collectively labelled WHOSIS, is now also available on-line. WHOSIS also contains "pointers" to virtually all of the information available from WHO.

Source: Patz, 1995.

The health hazards of climate change will entail a scale and timeframe with which the health sector has had little experience. The conventional concepts of prevention therefore require some modification. Regarding scale, some effects would not only be geographically widespread, but likely to arise indirectly via complex ecosystem changes. Detecting ecosystem changes that may affect health (for example, via vector-borne diseases) will therefore be important. For example, detection of non-human biological indicators that are predictive of increased risk of human disease, such as an increase in population densities of rodents or insects, would enable earlier preventive responses to be made.

A further challenge is posed by the time-scale. Many of the adverse health outcomes of climate change would occur gradually, over decades. Such delays could arise, firstly, because of the non-linear, threshold-based processes involved (for example, the eventual collapse of regional food-producing ecosystems, or the eventual overwhelming of local public health defences against vector-borne diseases), or, secondly, because of lengthy disease latency periods, as in the case of UV-induced skin cancer.

Table 10.1. Examples of greenhouse gas mitigation options*

Agriculture	• Reduced land conversion through improvement of farming techniques
	• Improved tillage to reduce fossil fuel combustion
	• Improved feed use for ruminants to reduce methane emissions
	• Reduced biomass burning to reduce methane emissions
Energy supply	• More efficient power generation
	• Natural gas turbines in place of oil or coal use
	• Gasification of fossil fuels prior to combustion
	• Combined heat and power production and district heating
	• Alternative energy sources: hydroelectricity; solar, nuclear or geothermal energy
	• Coal conversion technologies
Forestry	• Reduced deforestation with concurrent improvement in agricultural productivity [Note: tropical forests have the potential to sequester the largest quantity of carbon]
	• Regeneration of degraded lands for reforestation
Industry	• Cogeneration and steam recovery
	• Efficient lighting and electric motors
	• Alternative materials, e.g. replace concrete with wood
	• Use of solar power
	• "Heat cascading" to use energy byproducts of industrial processes
	• Recycling of energy-intensive materials
Human settlements	• Buildings with improved thermal integrity
	• Condensing furnaces and heat exchangers
	• Solar water heaters and insulated water storage
	• Financial incentives for conservation
	• Recycling
	• "Heat island" mitigation by planting shade trees
	• Utility regulations and building codes
	• More efficient cookstoves
Transportation	• Improved public transportation
	• Facilitation of cycling and walking
	• Urban traffic control for shorter transit times
	• Car-tuning programmes
	• Improved fuel-efficient engines
	• Improved energy-efficient design of ships and aircraft
	• Use of ethanol and methanol fuels

* Primarily carbon dioxide emissions reduction, unless otherwise indicated.

Source: IPCC, 1996b.

Given these considerations, a strong argument can be made for the use of a precautionary approach. Even if scientists were to obtain empirical data in the medium-term future about the health impacts of climate change, this could be too late for timely and effective intervention. Policy decisions in relation to climate change will therefore need to be taken on the basis of reasonable and prudent anticipation rather than demonstrable consequence.

Besides, precautionary measures aimed at reducing greenhouse warming will have many beneficial immediate effects on public health. Controlling air pollution and population growth, for example, would reduce stress — in the form of acid precipitation and excessive demand — on water resources. Such short-term health gains weigh favourably in the policy debate, which must consider potentially irrevocable longer-term health consequences simultaneously with vast uncertainties. The UN Framework Convention on Climate Change (UNFCCC), now ratified by 156 countries, has called for the reduction of national GHG emissions to 1990 levels by the year 2000. There is a clear precedent for this precautionary approach: namely, protection of stratospheric ozone. The protection of stratospheric ozone, although a politically, economically and technically simpler issue, set a clear precedent for such a precautionary approach. The 1987 Montreal Protocol and its later amendments aim to phase out use of ozone-destroying chemicals (especially chlorofluorocarbons) globally (see Box 2.4). Substantial biomedical research established the biological hazards of UVR and this stimulated the rapid endorsement of the Montreal Protocol by governments.

An equivalent primary prevention response with respect to GHG emissions is being sought via the UNFCCC. However, rapid substantial global reduction in GHGs may not be politically achievable. Changes in public perceptions of the potential adverse effects of climate change on health could play an important role in altering patterns of land and energy use to reduce GHG emissions. Raising public awareness of these potential health impacts will require action to educate the health professional community and to encourage media coverage of the topic.

Meanwhile, a certain level of unavoidable climate change is likely to be "in the pipeline". Preventive options of an adaptive (antidotal) kind must therefore also be considered.

Specific prevention options: localized adaptation to climate change

Many populations already suffer from ill health due to unsatisfactory living conditions and poor access to health care (WHO, 1995a). Such populations are likely to be especially vulnerable to many of the impacts of climate change, particularly since adaptive measures are likely to be beyond their financial and technical reach. In view of the uncertainties and the long time-scales that apply to these impacts, preventive measures in poor nations will be more feasible and more acceptable if they also meet or contribute to meeting immediate local needs. For instance, the development and large-scale introduction of a low-cost, solar-energy cooking device in developing countries would help to reduce GHG emissions and deforestation rates, and reduce indoor air pollution levels. It would also liberate working time, particularly for women who must often spend many hours each day collecting fuelwood. But whatever the economic or developmental level of the population in question, adaptations that meet both more general policy needs and specific local needs should be favoured. Thus, among developed country populations, transport policies that not only lead to lower levels of GHG emissions, but that also serve to reduce air pollution and traffic congestion and to improve physical fitness by promoting cycling and walking, would be highly appropriate (BMA, 1992).

In principle, there is a hierarchy of control strategies that can help to protect population health. Control options range from those that are population-wide, perhaps technology-based, to steps taken by individuals. Measures are (i) administrative or legislative; (ii) engineering-based/ technological, or (iii) personal (behavioural). Generally, legislation can potentially affect very large national or international populations. Technological advances, independent of administrative or legislative mandates, may also bring substantial benefits. For example, advances in sanitary treatment facilities have prevented an enormous burden of illness worldwide. Of course, in many instances, legislative or administrative mandates are required for the effective dissemination and population-wide adoption of such technology. Individual preventive responses to health threats are more highly varied than either legislative or technological options, but also far more unreliable. This is because misperceptions of relative health risks are widespread within general populations. As a result, appropriate preventive steps may be taken by selected groups only.

Population-level public policy measures

A number of population-level adaptive measures are outlined below. They exclude options that are energy-intensive (e.g. air-conditioning) and that would increase the build-up of GHGs, and options with potentially harmful side-effects, such as vector control by pesticide spraying or wetlands drainage, each of which can have serious adverse effects on human health and the environment.

Reduction of heat-related mortality and morbidity:

- Insulate buildings and other design features that reduce heat load.
- Plant trees within cities, and select materials with high albedo for roads, parking lots and roofs to reduce the urban "heat island" effect.
- Establish new weather watch/warning systems that focus on health-related adverse conditions, such as oppressive air masses (see Box 3.7).
- Create public education campaigns regarding precautions to take during heat waves and establish weather watch/warning systems.
- Implement work schedules for outdoor workers that avoid peak daytime temperatures.

Reduction of transmission of vector-borne diseases:

- Assess the vector-borne disease implications of development projects and policies that could increase vector-borne disease transmission, and where possible implement environmentally sound measures to prevent or mitigate such increases.
- Improve use of climate forecasts in order to stockpile vaccines, pesticides and other control tools more efficiently, and prepare measures for control of any anticipated disease outbreaks.
- Undertake public education to encourage elimination of human-made vector breeding sites (e.g. small water-containers).
- Promote the use of repellents, mosquito coils and insecticide-impregnated mosquito nets.
- Install mosquito and fly screens in buildings in endemic areas.
- Promote judicious use of pesticides and biological control methods.
- Undertake education campaigns to sensitize health care workers in geographically vulnerable areas.
- Expand the coverage of existing vaccination programmes aimed at elimination of diseases such as yellow fever, which are likely to increase in incidence following climate change.

Reduction of agricultural stresses:

- Reduce monocultural farming, to reduce dependence on chemicals for pest control.
- Promote land reforms that favour environmentally sound land use.
- Develop climate-adjusted plant species through genetic engineering.

Reduction of the impacts of extreme weather events and sea level rise:

- Maintain and strengthen emergency management and disaster preparedness programmes, including local public health service capacity to conduct rapid health needs assessments and to make psychological support interventions (WHO, 1992b).
- Implement engineering measures such as strengthening of sea-walls and ensure strict adherence to building regulations and standards in hurricane-prone areas.
- Adopt land-use planning to minimize erosion, flash-flooding, poor siting of residential areas, and deforestation.

Box 10.2. Integrated coastal zone management: the need for adaptive strategies

Means of countering or coping with the adverse effects of sea level rise will vary by locale, depending on specific vulnerabilities and costs. Inundation of low-lying islands or populated delta regions, loss of wetlands, and contamination of freshwater supplies are some of the major concerns associated with sea level rise. Adaptive options include: retreat (abandonment of land and other resources), accommodation (continued occupancy but changes in use of vulnerable areas) and protection (defence of vulnerable areas).

Unsustainable coastal development and increased demands on coastal zone resources may contribute more to coastal erosion than will sea level rise itself. At a minimum, such activities will make susceptible coastlines more sensitive to sea level rise. The potential short-term and long-term health impacts of sea level rise, such as threats to coastal freshwater quality and changes in the local hydrological cycle, would be best addressed through an integrated approach.

Coastal zones are important to human health not only on account of the environmental services they perform, but also because they sustain fisheries and support socioeconomic activities such as tourism. Their benefits in terms of human health are therefore both direct and indirect. Programmes addressing health-related environmental and resource preservation will need to undertake simultaneous assessment of economic development, land-use policy, water resource use, tourism, food production from fisheries, and waste disposal. Proposed policies must be considered within the context of financial constraints, and cultural and social appropriateness (for example, planned fishery restrictions may impede access to traditional fishing areas and risk creating social conflict), and political acceptability, particularly regarding resettlement of coastal populations.

Source: Bijlsma et al., 1996.

Reduction of general population vulnerability:

This is a general and fundamentally important adaptive strategy. Poorly resourced and politically non-powerful populations will be especially vulnerable to adverse climatic and environmental change. Interdisciplinary research involving the social and behavioural sciences as well as economics is needed to elucidate the critical sources and levels of vulnerability in such populations. Meanwhile, the broad adaptive strategies are:

- Reduce poverty and socioeconomic inequalities.
- Maintain biodiversity.
- Protect cultural resources.
- Carry out effective monitoring of environment, biological indicators, and human health.

The success of such adaptive responses, however, will depend upon the participation of local communities in the planning and implementation stages. If informed on the issues concerned, communities will have sufficient incentives to adopt the measures proposed, and particularly if they have contributed to the selection of these measures. At a technical level, an integrated environment management approach will often be necessary. Box 10.2 on integrated coastal zone management illustrates the long-term diverse strategies recommended for minimizing the human impacts of sea level rise.

Personal adaptive steps

Since personal adaptive steps are often unacceptable to many people, they are not likely to be fully effective at a population level. However, human behaviour sometimes changes dramatically following well-targeted, culturally-adapted dissemination of health information. Information on the health hazards of tobacco smoking is an example. Issues relating to climate change that could form the subject of effective health education programmes include:

- The need (particularly among the chronically ill and the elderly) to increase hydration and mineral intake levels during extremely hot weather.
- The need to reduce skin cancer risk by avoiding sun exposure, wearing protective clothing and sunglasses, or — particularly among children and adolescents — using sunscreen.
- The need to use mosquito nets impregnated with pyrethroid compounds or application of insect repellents to reduce malaria transmission (particularly among babies, children and pregnant women).

Additionally, warning systems, based on climate and weather forecasts, can be established to warn the public of an increase in a particular hazard and the need to adapt behaviour accordingly. Hay fever warning services and ambient UVR warning systems are already in place in some countries. The latter are operated in combination with public health educational campaigns to promote safe behaviours regarding sun exposure.

Balancing preventive and adaptive measures

Adaptive (or antidotal) measures offer varying, often limited, amounts of health protection, and may be temporizing measures only. For example, with regard to disaster response, basic short-term needs must be met by disaster preparedness programmes, yet the fundamental vulnerability of high-risk populations can be addressed only through long-term development programmes that strengthen community infrastructure (IDNDR Secretariat, 1994).

Many infectious diseases may not be amenable to preventive action (Haines & Parry, 1993). A vaccine is not yet available for human African trypanosomiasis and the risk of an adverse immune cross-reaction to one of the four viral subtypes currently precludes development of a dengue vaccine (Halstead, 1988). Similarly, parasite and vector resistance to therapeutic agents and pesticides, respectively, presents a continuing challenge. Anticipating any tendency for epidemics of new and resurgent infectious diseases to occur in a warmer environment will be difficult.

Clearly, in light of the shortcomings of adaptive measures, governments should focus on the upstream preventive option of reducing GHGs in support of the UNFCC.

Long-term planning: integrating health economics and development

The World Commission on Environment and Development defined "sustainable development" as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Subsequent discussions at the UN Conference on Environment and Development (UNCED) in 1992 demonstrated the political impossibility of separating the issues of environment from those of development (Williams, 1993). Besides, now that we better appreciate that environmental problems have wide-ranging, often indirect repercussions on health, separating human health concerns from those of development and the environment is not sensible. This in turn underscores the importance of developing a "primary environmental care" strategy — an environmental analogue for primary health care, the foundation for population health. Primary environmental care is a concept based on community-level activity, aimed at preserving the environmental resources on which the community in question depends and at promoting environmental health (Borrini Feyerabend, 1994).

Effective preventive strategies to reduce the health hazards of climate change will clearly require policy responses across many sectors. In common with strategies to reduce GHG emissions, they must include industrial emissions control, energy conservation measures, land-use policies to maximize CO_2 sinks, and population policies to minimize energy demand and destruction of natural CO_2 sinks. Policy-makers and scientists from many disciplines have already written extensively on such options and the fiscal, regulatory and voluntary means for carrying them out. Targeted sectors would include industry, transportation, forestry and agriculture. The potential health and environmental impacts of mitigation options, such as use of alternative energy sources, should also be examined by governments and research institutions. Many of these strategies are beyond the scope of this book but readers can refer to the *Second assessment report* of the IPCC (1996), the UNFCCC (1992), *Agenda 21* (Box 10.3; Keating, 1993) and various national plans. Table 10.2 outlines some of the recommendations so far made for limiting the health impacts of climate change.

Cooperation between developed and developing nations

Attempts to reduce GHG emissions and to protect human health are likely to fail if the world's natural CO_2 sinks continue to be depleted by deforestation. Likewise, preserving forests will not counterbalance the effects of fossil fuel combustion if the latter continues unchecked. Such

Table 10.2. Summary of recommendations for improving understanding and reducing the health impacts of climate change

Goals	Means
Empowerment of research institutions to pursue long-term, multidisciplinary research	• Education campaigns for the public health and policy-making communities about the health outcomes of climate change. • Incentives (financial or award-oriented) for researchers and institutions to undertake multidisciplinary, collaborative research. • Establishment of scientifically diverse panels within key international organizations to advise on needed research areas (CGCP, 1995). The current IPCC serves as a good example. • Expansion of electronic networking systems for international communication and data management.
Appropriate and increased research	• Systems-based analysis of climate/ecosystem/human health relationships. • Use of mathematical modelling and scenario-based predictions. • Integration of research methods and relevant monitoring.
Monitoring for early warning and quantification of health outcomes	• Incorporation of relevant health indices into the global observing systems (GCOS, GOOS and GTOS). • Establishment of comprehensive surveillance of anticipated changes in health trends, e.g. mortality from heat waves in sentinel cities, geographic distribution of vector-borne diseases at their current margins. • Linkages between present environmental monitoring and public health monitoring. • Use of Geographic Information Systems.
Preventive measures to avoid potentially adverse health outcomes of global climate change	• Precautionary action to reduce global greenhouse warming, including efforts to: i) reduce greenhouse gas emissions; ii) achieve cooperation between rich and poor nations; iii) implement sound population and development policies in the interest of both short- and long-term health benefits. • Primary prevention of anticipated health consequences on a regional or local level.

interdependence underscores the need not only for sectors to work together but for decision-makers and politicians to think and act in terms of a "global community". Energy issues and technology transfer can illustrate what the concept of a global community represents.

Today's developed nations emerged economically at a time when environmental integrity and human health were not recognized as being linked to the sustainability of natural resources. But although the adverse consequences of environmentally insensitive economic growth are now understood, developed countries cannot expect poorer nations to unilaterally forego the short-term profits to be obtained from use of their natural resources. In short, if these resources are vital to the health of the global community as a whole, governments with financial capacity should help pay for their preservation. The responses expected of developed and developing countries in the effort to mitigate climate change must be equitable.

Box 10.3. *Agenda 21*

Agenda 21 was the main document adopted at the United Nations Conference on Environment and Development in 1992. It illustrates the acceptance by many countries of the need to take a balanced and integrated approach to environment and development questions, and directly addresses global, social and environmental change, including climate change. Health is considered specifically in Chapter 6. *Agenda 21* also indicates how sustainable development might be achieved, and accordingly lists objectives and activities, and describes means of implementation. Thus it provides options for combating degradation of land, air and water, and conserving forests and biodiversity. One of the basic tenets of *Agenda 21* is that environmentally sustainable development is the most appropriate approach for dealing with poverty and environmental destruction. It stresses too that poverty can be alleviated by increasing the access to resources of impoverished communities.

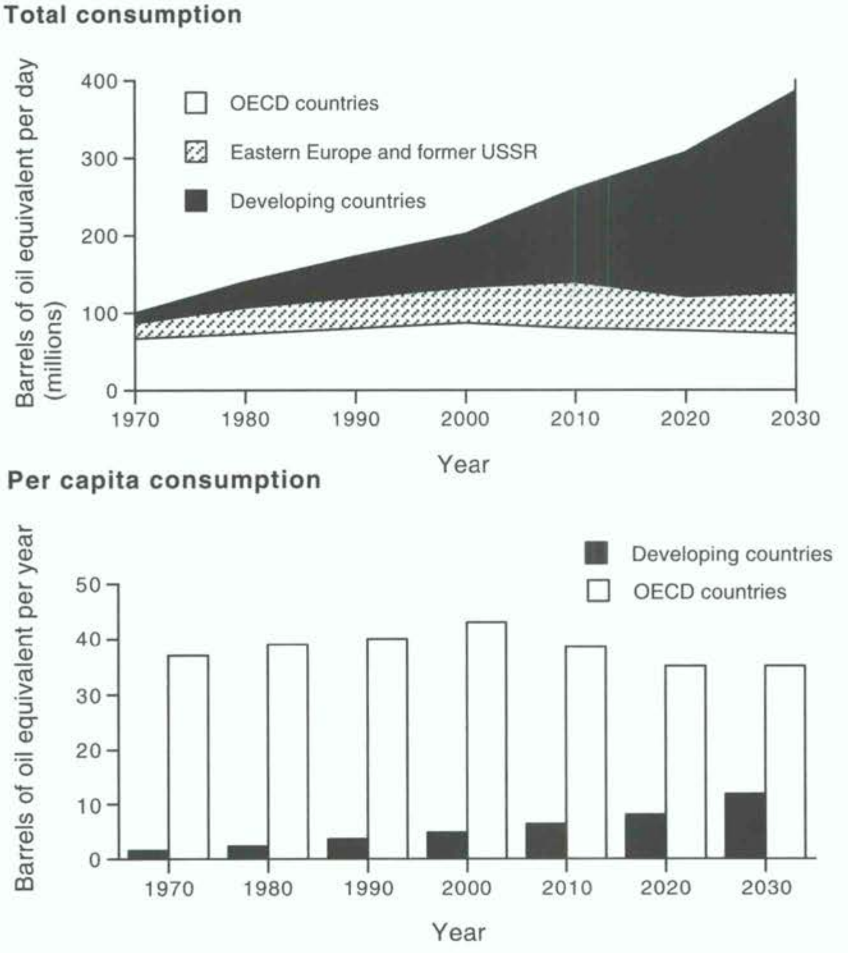
By adopting *Agenda 21*, developed countries recognized that they have a greater role to play in cleaning up the environment than do poor nations, who produce relatively less pollution. Additionally, the richer nations promised to increase funding to help other nations develop sustainably. *Agenda 21* points out, however, that developing countries need more than financial aid; they also need help in building the expertise and capacity to make and carry out sustainable development decisions. This will necessitate the transfer of information and skills.

Agenda 21 calls on governments to adopt national strategies for sustainable development, and to develop these with wide participation, including that of regional and provincial government, business, citizens groups, and nongovernmental organizations and the public. With UNDP support, WHO has initiated a country-level process to ensure that these strategies take public health considerations sufficiently into account. Thus *Agenda 21* considers that much of the responsibility for instigating change belongs to national governments.

Ecologically sustainable development will also only be possible if environmentally sound technology is transferred from developed to developing countries. This is because developing countries generally do not have the financial and technical means for creation of such technology. Indeed, as poorer nations undergo economic development, their GHG emissions will rise markedly if conventional technology continues to be used (Fig. 10.1). But if alternative, less energy-intensive technologies are promoted and transferred to developing countries at financially acceptable levels, pollutant emissions will be reduced and the global community as a whole will benefit. If such transfer does not occur, poorer nations will have no financial incentive to refrain from using cheap energy-inefficient technology or from harvesting their natural resources.

The sort of cooperation described above has already been seen in relation to the global problem of stratospheric ozone depletion and the 1990 London Amendment of the Montreal Protocol which established the Interim Multilateral Fund. This fund is designed to provide financial aid for developing countries in their efforts to shift their industries away from use of ozone-depleting substances. Similarly, the UNCED meeting established a Global Environmental Facility to assist

Fig.10.1. Energy consumption, by country group: total and per capita consumption, 1970–2030. (Note: an "energy-efficient" scenario is assumed, i.e. growth in total consumption of one to two percentage points below the trend rate.)



Source: World Bank, 1992. Copyright © 1992 by The International Bank for Reconstruction and Development/The World Bank. Reprinted by permission of Oxford University Press, Inc.

countries in redirecting their development process towards greater environmental sustainability and towards dealing with a broad range of global environmental change issues. These are small beginnings. To achieve further progress, shifts in economic philosophy will be necessary. For instance, the preoccupation of national governments with their GNP must be replaced by longer-sighted "full-cost accounting" of the value of functional ecosystems and of natural resources that, when considered within a global context, are more "profitable" and bring greater health benefits when left intact. Meanwhile, developed countries must work to reduce their consumption levels. In these countries, average personal consumption of energy and materials, and therefore GHG emissions per capita, are markedly higher than in developing countries. Approximately three-quarters of all energy-related GHG emissions come from the developed countries, although these countries account for only one-quarter of the world's population. Countries can also influence the course of global warming by adoption of appropriate land-use policies and selection of energy-efficient technologies.

Population growth, consumption patterns and emissions

The UN (1992) projects that world population will, under the most likely scenario, have increased from the 5.3 billion of 1990 to 6.3 billion by 2000, growing thereafter to 8.5 billion in 2025, 10.0 billion in 2050, and 11.2 billion in 2100. The World Bank's projections are very similar. Nearly all of this growth is anticipated to occur in today's developing countries. Increases in world population would mean increased global demand for energy, which, with current energy technologies, would result in increased GHG emissions. Population growth would also probably result in further deforestation and expansion of irrigated agriculture; both activities are sources of GHGs. Population policy is therefore becoming increasingly important for long-range planning within developing countries. Indeed, the industrial growth that would be necessary to meet population requirements, were population levels to continue to rise so rapidly, would place enormous additional stresses on the environment in future decades (World Bank, 1992).

Bongaarts (1992) has estimated that, over the next three decades, about half of the global increase in CO_2 emissions will be due to population growth. Then during the period 2025–2100, just under one-quarter would be due to population growth, with the rest due to increased economic activity. Throughout, the contribution of *additional* CO_2 from all developing countries, would be anticipated to exceed that of all the developed countries. This reflects the growing discrepancy in population numbers between the two categories of country. Population growth in developed countries, although much less than in developing countries, also contributes an important proportion of GHG emissions, since per capita consumption of fossil fuels is very much higher in these countries. Other analyses, while differing in certain assumptions and details, concur that a substantial share of the anticipated increase in emissions over the next several decades will be attributable to population increase.

Accordingly, international transfer of resources to the developing world to help curb population growth may be as beneficial as that directed at reducing deforestation, for example. Currently, only 1% of international donor aid is spent on family planning; a modest increase to 2–3% would suffice to make family planning accessible worldwide by around 2000 (Potts, 1994). But details of population policy should, at least for political reasons, be left to national governments; international attempts to impose uniformly structured programmes would be unacceptable. The more immediate health and economic gains resulting from family planning should continue to be the driving force behind any population policy. The prerequisite enhancement of women's social and economic status will need to occur within the appropriate local cultural framework. Discussion of the world population issue is fraught with cultural and political sensitivities. The issue itself is enormously complex. Some argue that several poor, densely populated and economically disconnected countries may have passed, or will soon pass, those population levels that their resource base can support both sustainably and independently (King & Elliott, 1993; King et al., 1995).

Meanwhile, a number of developed countries have far exceeded the capacity of their own territory to feed and support their population and so they rely on extensive imports which they have the wealth to purchase on the international market. Developed nations must show a commitment to reducing their consumption patterns, in particular by shifting to renewable energy sources.

Public health science in the 21st century

The health of human populations is influenced by a diverse mix of historical, cultural, demographic, socioeconomic, technological and environmental factors. Infectious disease incidence waxes and wanes in response to the rhythms of nature and local circumstances. Food supplies, and therefore nutritional status, are affected by natural disasters, by changes in the profile of pests and predators, by civil strife and war, and by patterns of commerce and trade. Chronic non-infectious diseases reflect much about the state of material development and its associated lifestyles (particularly with reference to diet, tobacco consumption, physical activity, and reproductive behaviour). In brief, human health is complex in its determination, and varies considerably over time.

This complex mix of influences upon population health profiles makes it difficult to project the proportional contribution of climate change to future trends in population health indicators. For example, malaria incidence rates are continually changing because of many non-climate influences, and their future trends, even in the absence of climate change, cannot be predicted with confidence. Estimating what a predicted increase in the global incidence of malaria due to climate change would represent as a proportion of the total future increase (or decrease) in incidence is therefore very difficult. However, the main point of this volume has not been to attempt specific and quantitative projections of the health impacts of climate change. Rather, it has sought to create an awareness that, in destabilizing the world's climate system and its dependent ecosystems, we are posing new and widespread risks to the health of human populations.

Integrated interdisciplinary research, and the development of validated predictive models to enable us to foresee likely impacts, are urgently needed. But we must appreciate the difficulties inherent in these new research tasks, as well as the long timescale over which many of the anticipated health-outcome events may emerge. Therefore, alongside an enhanced research effort we must adopt precautionary measures to abate the process of climate change.

Global and other large-scale geographically-based monitoring systems for the early detection of climate-induced changes in human health or in human disease precursors, must also be developed. For the reasons already mentioned, detecting signs of the initial emergence of such increases, such as changes in the distribution of malaria due to altered climate, or increases in the incidence of skin cancer due to ozone depletion, would not be easy. Health scientists need to address these questions, and how best to use information about shifts in the distribution of key indicator species (for example, rodents, insects, algae); their early sensitive response to climate change might presage changes in population health risks. More generally, environmental epidemiology must develop new research methods, complementary to the traditional dose–effect approaches currently dominating the field, to be applied to the assessment of health impacts of complex processes acting on timescales extending into the future.

Various health events have indeed occurred recently that might be early signals of global climate change. They include the substantially increased number of heat-related deaths in India, midwest USA and southern Europe in 1995, and changes in the geographic range of some vector-borne diseases. Could these be early indications of shifts in population health risk in response to aspects of climate change? Admittedly, attributing particular, isolated events to a long-term change in climate or weather pattern is unwise. Other plausible explanations exist for each of them, and a number of different factors may have combined to produce each event. But it is important that we begin to assess patterns of change in the various indices of human health that will provide early insight, and further assist the development of predictive modelling.

As we approach the 21st century, important tasks for public health science include understanding the ways in which climate change and other global environmental changes might influence human population health, and developing interdisciplinary links and modelling skills that will improve our capacity to predict such impacts. Meanwhile, all of us, but especially policy-makers, must come to terms with the application of precautionary approaches to these large, uncertain, but potentially serious hazards to human population health. A venerated and ancient tradition in health care practice is "primum non nocere" — first, do no harm.

Chapter by chapter summary

Introduction

As the science of human-induced climate change becomes clearer, the importance of addressing the possible impacts of climate change increases. Initial concerns about the impacts of climate change tended to focus on material and ecological systems important to human society — human settlements, coastal zones, agricultural land, forests and fisheries. More recently, recognition has grown that climate change could affect the health of human populations adversely. But the complexity of this "environmental hazard" and the unavoidable uncertainties about future climatic (and other global environmental) processes, make assessment of its potential health impacts extremely difficult.

Evidently, focusing on the more familiar and more easily quantifiable risks associated with potential climate change would simplify this task. Such risks include increased numbers of deaths from heat waves and higher incidence of trauma following more frequent occurrence of floods and storms. In the case of stratospheric ozone depletion — which is occurring concurrently with climate change — higher incidence of skin cancer is the most obvious example of a familiar, quantifiable risk. However, in the longer term, sustained changes in climate and in climate-sensitive natural systems would lead, via a number of routes, to many different impacts of public health significance. Such changes would include shifts in patterns of infectious disease, especially vector-borne diseases such as malaria and dengue, regional declines in food production, and population displacement due to rising seas, decreased agricultural productivity, and weather disasters. Combinations of existing factors such as readily dispersed infections, malnutrition and social stress, especially among displaced and migrating groups, could amplify these health impacts.

Three aspects of this topic therefore bear emphasis: namely, its scale, context and uncertainty. Firstly, the anticipated health risks are not of a localized kind; they will be large in scale and impinge on whole populations. Secondly, the risks cannot be categorized as simply "more of the same" (for instance, more heat waves, more air pollution). Rather, they would occur principally via *indirect* pathways, via disturbance of natural systems. This means that they should be assessed within an ecological framework. Thirdly, forecasting these risks entails adoption of a long timeframe.

This volume brings together current knowledge and ideas pertaining to climate change and forecasts of its health impacts. It also considers research methods and priority areas for research, as well as monitoring needs.

The climate system

Climate is the product of interactions between the atmosphere, ocean, land surface and ice cover. Shifts in global climate occur as a result of external factors, such as changes in the balance at the outer edge of Earth's atmosphere between incoming short-wave solar radiation and outgoing terrestrial long-wave radiation. Some terrestrial infrared radiation is absorbed naturally by greenhouse gases (GHGs) in the lower atmosphere. As a result, less energy is lost to space than would have occurred in their absence, and Earth's average surface temperature is approximately 15°C, or about 33°C higher than it would otherwise be. But perturbation of this process — known as radiative forcing — is now occurring and upsetting the Earth–atmosphere energy balance. This is because outgoing terrestrial radiation has been reduced, following increases in GHG levels. Radiative forcing has therefore increased and could be resulting in enhanced warming.

Emissions of GHGs, including carbon dioxide, methane, nitrous oxide (N_2O) and halocarbons, have been rising dramatically ever since the beginning of the Industrial Revolution (1750–1800), largely as a result of increases in fossil fuel combustion. This is now becoming a global problem because of the long atmospheric lifetimes and global dispersion of these gases. However, over and downwind of regions of industrial activity and biomass burning, tropospheric aerosols are probably offsetting some of the positive radiative forcing of GHGs. This is because they reduce radiative forcing both *directly* by scattering and absorbing radiation, and *indirectly* by modifying the properties of clouds. Unlike GHGs, tropospheric aerosols have very short lifetimes.

Earth's global mean surface temperature has increased by about 0.3–0.6°C during the past century. This observed increase accords with the latest climate model simulations, which combine historical accumulation of GHGs, cooling caused by industrial aerosols, and concealed warming due to heat absorption by the oceans. Many meteorologists are now confident that a human influence on global climate is detectable.

Future human-induced climate change is forecast by constructing mathematical models of the climate system. GHG and aerosol precursor emission scenarios, based on assumptions about population growth and future social and economic developments, are important inputs. General circulation models (GCM) are complex global climate models and as such the most powerful tools available for making realistic estimates of global climate change. GCM experiments indicate that global mean surface temperature will have increased by 1–3.5°C by 2100. They also indicate changes in precipitation patterns. For example, higher frequency of heavy precipitation events, which could lead to increased flooding, is predicted. But for regions currently prone to drought, it appears that droughts could become longer lasting and more severe. Additionally, global mean sea level is predicted to rise by between 0.2 m and 1.0 m by 2100, and would be expected to continue to rise for several centuries even if GHG levels were to be stabilized. As for storminess, although GCM model experiments do not agree on global systematic change, the possibility of regional systematic change cannot be excluded.

Meanwhile, via a quite distinct process, various human-made gases (particularly the halocarbons and N_2O) have reduced stratospheric ozone levels, especially at higher latitudes. As a result, a greater proportion of solar ultraviolet radiation (UVR) now reaches Earth's surface, presenting a hazard to human health and biomass production.

The rate of climate change will determine the consequent degree of stress experienced by biological systems and human society, and the extent to which they must adapt. But beyond these changes in mean values, any change in the pattern of extreme weather events (which include droughts, heavy precipitation, floods and storms) would produce significant impacts. In view of the complexity of the climate system, with its non-linear and feedback processes, global and especially regional surprises can be expected.

Heat, cold and air pollution

Variations in weather affect human health. For instance, stressful hot weather episodes are a known cause of short-term mortality excesses. A change in world climate, including an increase in the frequency and severity of heat waves, would obviously exacerbate such excesses. Conversely, milder winters would result in some decreases in winter mortality. The extent to which these decreases would offset the summertime increases, and how this balance would vary between different populations, remain uncertain though. Furthermore, it is not yet well understood how local circumstances might modify the longer-term health impacts on local populations of global climate change. It is clear, however, that substantial physiological and cultural adaptation can occur in response to climatic conditions. But on balance, evidence suggests that increases in "acute" mortality in response to more frequent hot weather episodes would outweigh decreases in winter-related mortality.

The role of cultural factors with respect to the impact of hotter weather upon human health and mortality also requires clarification. How much would air-conditioning, where available, mitigate the effects of temperature increases? Could changes in urban design help to counteract the health effects of climate change? Could the increasing proportion of elderly persons, combined with the adverse health effects of climate change, cause shifts in heat-related mortality rates? To what extent would air pollution levels influence mortality via their interaction with changing weather variables? What proportion of the excess of acute-episode deaths would be attributable to a brief forward displacement in time of imminent death in already sick and frail persons?

Air pollution also has a range of serious health consequences, and an increase in temperature would increase temperature-dependent formation of secondary air pollutants, particularly tropospheric ozone. In short, climate change could entail increased frequency of periods of very hot weather combined with increased pollutant concentrations. These could have synergistic impacts on health by enhancing the biological impact of both types of exposure. But in temperate regions, higher temperatures might reduce the tendency for people with bronchitis and emphysema to experience exacerbation during winter. However, seasonal allergic disorders might rise in these regions because of increased production of pollen and other biotic allergens. Further research is needed to clarify the relative effects of coexistent stressful weather and air pollution upon health.

Effects on biological disease agents

Many of the biological organisms and processes linked to the spread of infectious diseases are influenced considerably by climatic factors. Infectious diseases include vector-borne diseases, many of which are a major source of illness and death in developing countries.

The distribution and abundance of vectors and intermediate hosts are determined by various physical factors (temperature, precipitation, humidity, surface water availability and wind) and biotic factors (vegetation, host species, predators, competitors, parasites and human interventions). An increase in ambient temperature is anticipated to cause net increases in the geographic distribution of vector organisms such as malarial mosquitos, although some localized decreases may also occur. At the same time, temperature-related changes in the life-cycle dynamics of vectors and pathogens would increase the potential transmission of vector-borne diseases such as malaria, dengue and onchocerciasis. Incidence of trematode infections, including schistosomiasis, may also rise due to climate-related changes in transmission dynamics and effects on the abundance of snail intermediate hosts. Climatic factors, in addition to multiple human, biological and ecological determinants, also affect the emergence and resurgence of infectious diseases. Infectious disease surveillance and prevention will therefore remain important components of the maintenance and promotion of public health.

Malaria incidence, as has been well documented, is sensitive to local changes in annual temperature and precipitation. Considerable research has therefore been undertaken to investigate the impact that climate change could have on the dynamics and transmission of this disease. Simulations with first-generation mathematical models project an increase in malaria incidence in Indonesia of 25% by 2070 and — with a highly-aggregated model — an increase from around 45% to around 60% by the latter half of the next century in the proportion of the world population living within the *potential* malaria transmission zone. Although the projected increase in potential transmission concerns mostly 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 baseline total of 500 million cases by 2100) would occur primarily in tropical, subtropical and less well protected temperate-zone populations currently at the margins of endemically infected areas.

Some increases in non-vector-borne infectious diseases, such as cholera, and other food-related and water-related infections could also occur. Such increases would be most likely in tropical and subtropical regions, following climatic impacts on temperature and water distribution. Other climate-related ecological disturbances such as algal blooms would influence the transmission of some infectious agents and the production of those biotoxins that contaminate the aquatic food chain.

Climate, food production and nutrition

The *global* aggregate effect of climate change on agricultural production is likely to be small to moderate. Modelling climate change impacts on regional food supplies is difficult for a number of reasons, including:

- uncertainties in regional climate-change predictions;
- the fact that our understanding of certain agricultural processes, in particular the "fertilization" response of different crops to increased levels of atmospheric CO_2, and the likelihood of altered patterns and distributions of plant diseases, weeds, insects and pests, remains incomplete;
- uncertainty regarding the potential for adaptation of agricultural practices;
- uncertainty regarding the potential of regional and global trading systems to ensure more equitable food distribution.

Moreover, major system feedbacks, such as interactions between soil condition, climate, vegetation cover, and cropping practice, and interactions between international market conditions, altered local yields, and changing labour and input prices, have not yet been modelled adequately.

Studies predict consistently that climate change will have significant regional impacts on agricultural yield. Some areas will gain; others will lose. Some mid-continental drying in temperate zones such as the mid-west USA, southern Europe and Ukraine may occur, but the most negative effects are foreseen at lower latitudes, in poorer tropical and semi-tropical countries, especially those reliant upon rainfed, non-irrigated agriculture. At-risk populations include those of sub-Saharan Africa, south Asia, east Asia and south-east Asia, and some Pacific Island nations. A reduced food supply would increase hunger and malnutrition levels in some vulnerable populations, with adverse effects on pregnancy outcome and child growth and development. General biological resilience, to infection for instance, could also be affected negatively.

Various types and levels of technological and socioeconomic adaptation to climate change are possible. However, the extent to which such adaptation could be undertaken would depend on financial costs, access to technology, and biophysical constraints such as water availability, soil characteristics and genetic diversity. Recent national studies show that the increased costs of agricultural production under climate change scenarios would be a serious economic burden for some developing countries. The potential effects of changes in water temperature, ocean currents, nutrient flows and surface winds upon fisheries are less well understood.

Extreme weather events

Extreme weather events, such as floods and droughts, frequently have serious impacts on human health. They also often trigger human disasters, which may in turn have psychological sequelae, in some cases leading to post-traumatic stress disorder. Moreover, population vulnerability to extreme weather events is increasing due to rapid population growth, urban settlement (particularly in coastal areas), and persistent poverty.

The extent to which the frequency of extreme weather events will be altered by climate change remains uncertain, although a changed pattern of floods and droughts is anticipated. Many climate models suggest, for instance, that precipitation will increase at high latitudes and that in some low-lying areas sea level rise could present a major risk. As well as the possibility of drowning and injury, resultant flooding could damage agricultural land and settlements, and cause contamination of drinking-water. For regions at low latitudes, climate change models predict a reduction in precipitation and an increase in evapotranspiration. This would have the effect of decreasing run-off. Droughts could also become more frequent.

In Africa in particular, droughts have often caused large numbers of deaths among humans and animals, and displaced populations. In arid and semi-arid regions, even relatively small reductions in precipitation can have large, non-linear, long-term effects. Thus any sustained decrease in precipitation could have serious impacts on human health, both directly as a result of reductions in drinking-water supplies and indirectly by affecting food production adversely.

Storms accompanied by high winds may also increase following climate change. Direct effects of storms include fractures and head injuries. Indirect effects include damage to local infrastructure.

Sea level rise

Global mean sea level is projected to rise by between 0.2 m and 1.0 m by 2100. The current "best estimate" thus predicts a rate of rise in sea level that is two to three times greater than that experienced during the past 100 years. However, changes in sea level will not occur uniformly around the globe. Regional responses could diverge from the mean by a factor of two to three due to regional differences in warming and changes in ocean circulation. Additionally, ongoing geological and geophysical processes cause vertical land movements and these would affect local and regional sea level changes.

More than half of the world's population now lives within 60 km of the sea and the average growth rate of this population is higher than that of the global population. Coastal zones are under increasing pressure from human settlements, infrastructure development and industrial activities, and thus undergoing rapid change and experiencing damage to shorelines, coastal wetlands and, in many areas, to coral reefs. Sea level rise could therefore have significant additional impacts on coastal zones. Deltaic regions also tend to be densely populated and are likely to be similarly vulnerable. Sea level rise might also increase the vulnerability of coastal zones to the impacts of extreme weather events such as very high precipitation and storm surges.

Sea level rise could have a range of health impacts, other than those associated with population displacement, including saltwater intrusion and contamination of water supplies, changes in the distribution of vector-borne disease, increases in death and injury due to flooding, and reduced nutrition levels due to loss of agricultural land and/or declines in fish catches. A number of factors could influence the severity of these impacts. Local subsidence due, for example, to excessive extraction of groundwater could amplify them, whereas flood control and storm protection programmes and provision of clean water and sanitation services could reduce them. More research is required to assess these potential impacts and to determine how they could be influenced by interactions with the other aspects of climate change such as increased precipitation and extreme weather events.

Stratospheric ozone depletion

An increasing proportion of solar UVR is reaching Earth's surface due to stratospheric ozone depletion. Increased UVR levels have now been documented for mid-latitude and high-latitude locations. Although the basic cause of stratospheric ozone depletion is distinctly different from that of the build-up of GHGs in the lower atmosphere, there are many physical and chemical interactions between these two phenomena. Furthermore, climate change and higher exposure to UVR may combine interactively in influencing human health and some of its environmental determinants.

Higher UVR exposure is expected to cause an increase in the incidence of skin cancer (especially non-melanotic skin cancers) in light-skinned populations. It could also increase the incidence of eye lesions (such as cataracts) and possibly cause weakening of the immune system (which could have implications for infectious disease risks and for responsiveness to vaccination). Increased ground-level UVR may also affect human health indirectly via adverse effects upon animal and plant biology, and in particular by impairing terrestrial and aquatic food chains.

Research and monitoring

The diverse and often non-linear patterns of biological response to climate change and its sequelae indicate that simple quantitative models will often not be sufficient for forecasting its potential health impacts. The significant variation in vulnerability of populations around the world, and the ever-changing configuration of influences upon their health profile, also render the forecasting of climatic influences upon health highly problematic.

For some impacts, extrapolation from well-documented relationships, such as that between heat waves and mortality, can yield useful projections. For others, extrapolation from recent localized climate-related changes in health, such as increased incidence of certain infectious diseases following regional climate change, may be informative. But generally, the complexity of the predictive task requires use of integrated mathematical models, drawing on the insights and skills of various scientific disciplines. However, the use of such models to forecast health impacts is still at a relatively early stage. Current models lack regional and local resolving power, omit certain categories of variables, and have not yet been fully validated. Further problems arise with respect to epidemiology. This is the key quantitative science of public health, but it is primarily oriented around empirical studies of current or recent health experiences within populations. It thus has relatively little experience in analysing complex and non-linear causal constellations. Nor has is it yet developed the tools for futuristic analysis of impending global health risks on an *if–then* basis.

The ecological context within which many of the health impacts of climate change would arise must also be taken into account. For example, changes in arthropod-vector habitats or marine vegetation could have significant effects on the incidence of certain infectious diseases. Risks to population health must therefore be conceptualized and studied within an appropriate ecologically-based framework which allows for evaluation of multiple ecological stress factors and their impacts on a variety of species within an ecosystem.

Given the serious threat to human health that global climate change represents, monitoring of changes in health status, and their ecological precursor phenomena, is strongly recommended. Fortunately the advent of remote sensing and geographical information system technologies is greatly assisting large-scale data collection and analysis. Such integrated monitoring will provide early evidence of the health impacts of climate change, and facilitate advance decision-making on climate change mitigation and action to prevent further health impacts, as well as retrospective evaluation of such action.

The recently-established Global Climate Observing System (GCOS) (a collaborative effort between WMO, ICSU, the IOC of UNESCO, and UNEP) is intended to be a long-term global observation system for the close monitoring of climate, climate variability and climate change. GCOS has an oceanic component (GOOS), and a terrestrial component (GTOS). The system aims to provide a link between data collectors and the user community. The health sector should take this opportunity to formulate and negotiate its requirements pertaining to climate monitoring coverage. But before this can occur, it will need to be become more aware of the potential use of climate monitoring data for health impact assessment.

In some instances, monitoring of the health impacts of climate change can be promoted by ensuring that climate monitoring data is incorporated into existing health monitoring programmes. Such a programme-driven approach will be most supportive for planning and decision-making in geographic areas that are particularly sensitive to the impacts of climate change.

The role of WHO and other UN agencies regarding climate change research and prevention is threefold:

- to secure the involvement of developing countries and to assist them by providing technical support;
- to act as a catalyst for climate-related programmes;
- to periodically evaluate progress in climate–health research, monitoring and capacity-building.

The climate agenda, adopted by the WMO Congress in June 1995, provides the interagency framework for aligning the various international climate programmes and ensuring that human health is given sufficient attention.

Finally, the role of the social sciences in analysing the impacts of and possible means of adapting to climate change should be stressed. In particular, given the long-term nature of climate change, understanding human and societal behaviours is very important. Similarly, "environmental" and "ecological" economics, which have emerged recently, are of much relevance since they seek a sustainable balance of values, interests and behaviours and can therefore serve as useful tools for analysis and selection of adaptive, mitigative and preventive measures.

Recommendations and conclusions

Over the coming decades climate change could have a variety of impacts, mostly negative, on human health. In the longer term, many of these will be likely to occur via indirect mechanisms such as alteration of infectious disease transmission, reductions in regional agricultural production, and exacerbation of some types of air pollution. Furthermore, migration and socioeconomic disruption due to sea level rise and/or extreme weather events (or the depletion of natural resources due to other components of environmental change), could also inflict a range of adverse health effects.

Research and policy priorities for addressing and mitigating this potentially large-scale public health hazard include:

- elucidating the human dimension of climate–health relationships, particularly concerning the nature and magnitude of community vulnerability to the health impacts of climate change and the scope for the development and implementation of adaptive response strategies;
- establishing the role of climate and climate change in global environmental change processes that affect human health, namely, deforestation, desertification, depletion of freshwater resources, loss of biodiversity and species migration;
- promoting interdisciplinary research and increased support for research institutions committed to investigation of climate–health relationships within an interdisciplinary framework;
- developing new methods of predictive assessment such as systems-based analyses of climate, ecosystem and human health relationships;
- improving monitoring of the health of human populations and of biological indicators in the environment so that longitudinal data can be established and health risk assessment and policy decision-making enhanced;
- adopting preventive measures which have short-term ancillary health benefits and enhance long-term environmental sustainability.

Effective long-term planning to prevent or mitigate climate change will require consideration of economic and development strategies, and of more specific health strategies. Health strategies will need to incorporate both mitigative and adaptive responses. International health surveillance and monitoring systems already in place will need to be strengthened and improved. This will contribute to dealing with present as well as future health problems. Health impact monitoring should not, however, be permitted as an excuse for "wait-and-see" approaches in dealing with mitigation and prevention issues described in the UN Framework Convention on Climate Change. Research, monitoring, and formulation of preventive options should all be pursued urgently.

Glossary

This glossary has been produced to be of help to readers of this particular text. It has been compiled with the aid of a number of glossaries and dictionaries in the area of climate change, air pollution, human health and biology, and as such should not be considered an approved glossary of any of the organizations that contributed to the production of this text.

Terms in bold that are included in a definition are themselves defined separately.

absolute humidity: the mass of water vapour in a given volume of air.

acclimatization: physiological and/or behavioural **adaptation** to variations in climate.

acid rain: precipitation that has a **pH** lower than about 5.0, the value produced when naturally occurring carbon dioxide, sulfate and nitrogen oxides dissolve into water droplets in clouds. Increases in acidity may occur naturally (e.g. following emission of **aerosol**s during volcanic eruptions) or as a result of human activities (e.g. emission of sulfur dioxide during fossil fuel combustion).

action spectrum: measure of the relative effectiveness of different wavelengths within the **spectral region** of a study to produce a given response (e.g. **DNA** damage).

acute effect: short-lived effect (in contrast to **chronic effect**).

acute mortality: used here to refer to increases in daily **mortality** associated with short **exposure**s to stressful climate conditions and/or air pollutants. Many of the deaths occur in highly susceptible individuals.

adaptation: spontaneous or planned adjustment in response to or anticipation of changes in climate conditions. Adjustments can be made to practices, processes or structures.

aerosol: suspension of extremely small liquid or solid particles in the **atmosphere**. Sulfate aerosols are present in the **troposphere** due to the industrial emission of sulfur dioxide. They are important as a source of negative **radiative forcing** and **acid rain**.

aerosol transmission: person-to-person transmission of disease agents via **aerosol**ized droplets. Many respiratory diseases are transmitted in this way.

***Agenda 21*:** document from 1992 UN Conference on the Environment and Development containing specific objectives and action plans for a "new global partnership for sustainable development".

air mass: synoptic meteorological characterization of the entire body of air and its qualities. Air masses can be determined empirically using a combination of meteorological variables that include temperature, **relative humidity**, wind speed, wind direction and barometric pressure.

albedo: whiteness; a measure of the reflecting power of an object (e.g. Earth), expressed as the proportion of incident light it reflects. Clouds, ice and snow have a high capacity to reflect solar radiation and are therefore said to have a high albedo.

aldrin: an insecticide (which is a special kind of pesticide, lethal to insects).

algal bloom: abnormally increased **biomass** of algae in a lake, river or ocean.

amplify/amplifier: an amplifying **host** is one that epidemiologically serves the function of increasing the size of the pathogen population.

anaplasmosis infection: chronic infection of ruminants caused by a protozoan parasite, *Anaplasma*, transmitted by ticks, horse flies, and mosquitos.

anomaly: event that is a deviation from normal behaviour, and that has a finite but usually very low probability of occurring.

anthropogenic: caused or produced by human activity.
anthropometry: measurement of the human body.
anticyclone system: system of winds that rotates about a centre of high atmospheric pressure (clockwise in northern hemisphere, counter clockwise in southern hemisphere).
antigen: any molecule capable of being recognized by an antibody or T-**lymphocyte** receptor. Usually a protein molecule that the body's immune system recognizes as "foreign".
apparent temperature: quantitative measure of the temperature perceived by the human body. It is a composite of temperature, humidity, and, in some cases, wind.
arboviruses: viruses transmitted by arthropods (arbo = arthropod borne). Examples include the causative agents of dengue, St Louis encephalitis, western equine encephalitis and yellow fever.
arenavirus: family of viruses, some of which are pathogenic to humans, causing epizootic and **epidemic haemorrhagic** fevers. Rodents are the natural **reservoir** of all arenaviruses. Infection in humans occurs via inhalation or ingestion of materials contaminated with rodent excreta. The family includes Junin virus which causes Argentine haemorrhagic fever and Machupo virus which causes Bolivian haemorrhagic fever.
arid region/zone: ecosystems which receive less than 250 mm precipitation per year.
atmosphere: gaseous envelope that surrounds Earth and which is subdivided into the **troposphere**, **stratosphere** and **mesosphere**.
balantidiasis: infestation of the large intestine with the parasitic protozoa *Balantidum coli*, usually through consumption of food or water contaminated with pig faeces. Symptoms include diarrhoea and dysentery.
basic reproduction rate: a quantitative measure of the ability of a **vector**-borne disease to spread. It is defined as the number of new cases of a disease that will arise from one current case when introduced into a non-immune host population during a single transmission cycle. Hence this rate will apply only during the initial stages of spreading, since once the population has acquired some immunity, the rate of disease spread will slow.
bioclimatic threshold: minimum temperatures and humidities required by arthropod vectors for year-round survival, and which limit their geographical distribution.
biodiversity: the totality of genes, species and **ecosystem**s.
biofuel: renewable hydrocarbon fuel, usually alcohol, e.g. methanol, ethanol, derived from corn (maize) and other grains.
biological indicator: a change in the distribution and biological activity of a species or a complex of different species which reflects an environmental impact on an **ecosystem**.
biomarker: biochemical, cellular or molecular indicator of **exposure**, health effects or **susceptibility**. Biomarkers can be used to measure biologically effective dose, early biological response, altered structure or function of cells, tissues and organ systems, and susceptibility.
biomass: the quantity or weight of living and dead plant and animal material in a unit of area.
biomass energy: potential **biomass** sources of energy, such as municipal solid waste, industrial and agricultural residues, existing forests and biomass plantations.
biome: biological subdivision that reflects the ecological and external character of the vegetation in question. Biomes correspond approximately with climatic regions. Examples include: tropical rain forest biome, desert biome, tundra biome.
biometeorology: the study of the impacts of weather on biological phenomena, such as animal and plant distribution, population fluctuations and human well-being and health.
biosphere: the part of Earth and its **atmosphere** in which living things are found.
biotoxin: toxin produced by a living organism.
biotype: group of organisms that are genetically identical or very similar.
brackish: salinity intermediate between that of seawater and fresh water.

C_3 plants: plants that produce a three-carbon compound during **photosynthesis**. Includes most trees and agricultural crops, e.g. rice, wheat, soybeans, potatoes and vegetables.

C_4 plants: plants mainly of tropical origin, that produce a four-carbon compound during **photosynthesis**, e.g. sorghum, sugar cane, maize and millet.

CD4: a cell surface protein, usually on helper T-**lymphocyte**s, that recognizes foreign **antigen**s on antigen-presenting cells.

CO_2 fertilization: enhancement of plant growth as a result of elevated atmospheric carbon dioxide (CO_2) levels.

cachexia: condition of abnormally low weight, weakness and general bodily decline associated with chronic disease, e.g. malaria, tuberculosis, cancer.

Candida: genus of yeast-like fungi commonly found in nature; a few species are isolated from the skin, faeces, and vaginal and pharyngeal tissue, but the gastrointestinal tract is the source of the single most important species *C. albicans*.

carbon sink: repository for carbon dioxide (CO_2) removed from the atmosphere. Oceans appear to be major sinks for storage of atmospheric CO_2.

carrying capacity: the number of individuals in a population that the resources of a habitat can support at a given point in time.

case–control study: observational epidemiological study in which persons with a disease or other outcome variable (the "cases") are compared with a suitable control group of persons without the disease or outcome (the "controls"). The relationship of an attribute to the disease is examined by comparing the diseased and non-diseased with regard to how frequently the attribute is present, or, if quantitative, the levels of the attribute, in each group.

cataract: opaque condition of the lens of the eye.

cercaria (cercariae plural): the free-swimming **trematode** that emerges from its snail **host**; it may penetrate the skin of a final host (as in *Schistosoma* of humans), encyst on vegetation (as in *Fasciola*), in or on fish (as in *Clonorchis*), or penetrate and encyst in various arthropod hosts.

chlorofluorocarbons (CFCs): halocarbons that are major **greenhouse gas**es. CFCs are of human origin and have long atmospheric lifetimes (more than 100 years). They are destroyed only by **photolytic destruction** in the **stratosphere** where they cause **ozone** depletion. Under international agreements, the use of CFCs is being phased out completely.

chronic effect: long-lasting effect (in contrast to an **acute effect**).

chronic disease: lasting, lingering illness.

ciguatera fish poisoning: illness caused by toxins produced by certain **dinoflagellate** species. The toxins may become concentrated in higher predators, such as reef fish, which may remain toxic for more than two years after becoming contaminated. The symptoms of acute poisoning include gastrointestinal distress, followed by neurological and cardiovascular symptoms which are rarely fatal. Ciguatera is considered a major health and economic problem on many tropical islands where fish forms a large part of the diet.

***cis*-isomer:** isomer having two atoms or groups on same side as plain of symmetry.

climate sensitivity: in IPCC reports, climate sensitivity usually refers to the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric CO_2 concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing.

climatic droplet keratopathy: degenerative condition of the corneal stroma (fibrous layer of the tissue of the cornea) with droplet-shaped deposits, which usually affects both eyes. It is a significant cause of reduced vision and blindness in older people worldwide and is more common in those areas of the northern hemisphere where snowfall persists late into summer, and in areas of sand and desert at other latitudes.

cold front: interface between an advancing cold air mass and a retreating warm air mass. A front is thus an interface between two air masses of differing temperatures.

confounding (confounding variable): variable that is associated with the **exposure** under study and is a risk factor for the disease in its own right (i.e. it is not just an intermediate variable on the causal path between exposure and the disease).

contact hypersensitivity response: form of cell-mediated **delayed-type hypersensitivity** immune response that occurs where **antigen** is applied to the surface of the skin. In studies on experimental animals this response is often induced by contact with the chemical DNCB.

coral bleaching: occurs when coral organisms (polyps) die or migrate away from a coral reef to the extent that it loses colour. Mass-bleaching events have been associated with small increases in sea temperature.

cutaneous myiasis: infection of the skin caused by larvae of dipterous insects.

cyanobacteria: microscopic bacteria found as free-floating **plankton** in freshwater and marine **ecosystem**s. Many species produce potent **biotoxin**s. Cyanobacteria were previously known as blue-green algae.

cyclone: a system of winds blowing spirally inwards towards a centre of low barometric pressure.

cytokines: glycoproteins that bind to cell surface receptors on immune cells to trigger their differentiation, proliferation or function. Cytokines are involved in regulating all aspects of the immune response.

cytotoxic: that which damages or destroys cells. For example, cytotoxic T-**lymphocyte**s recognize and kill foreign cells as part of the immune response.

DNA (deoxyribonucleic acid): the genetic material for nearly all living organisms. The genetic information is contained in the sequence of bases along the molecule; changes in DNA cause mutations.

DNA probe: in molecular biology, method by which a known sequence of **DNA** is detected.

delayed-type hypersensitivity response: a localized inflammatory reaction to certain types of **antigen** (whether applied to the skin or injected), induced by **cytokine**s which are secreted by a subpopulation of helper T-**lymphocyte**s. The cell-mediated response plays an important role in defence against intracellular pathogens and contact antigens and is not usually tissue-damaging.

demersal: bottom-dwelling.

demographic entrapment: the predicament of a population that has exceeded the **carrying capacity** of its local or regional **ecosystem** and that cannot afford to import food or other essentials. People caught in a demographic trap either become dependent on external food aid or must emigrate as environmental refugees, or both.

demography: the study of populations, especially with reference to size and density, fertility, **mortality**, growth, age distribution, migration, and the interaction of all these with social and economic conditions.

desert: an **ecosystem** that receives less than 100 mm precipitation per year, has very permeable soil, and poor and discontinuous plant and animal life.

dewpoint temperature: temperature at which water vapour starts to condense.

diapause: period of suspended growth or development and reduced metabolism in the life cycle of many insects, when organism is more resistant than in other periods to unfavourable environmental conditions.

diatom: one of a class of microscopic algae. There are over 10 000 diatom species, most of which are single-celled. Diatoms are one of many types of **phytoplankton**.

dinoflagellate: an order of protozoa, closely allied to brown algae and **diatom**s. They are sometimes classified as algae. Typically, dinoflagellates have two flagella, and most are **plankton**ic.

diurnal temperature range: the difference between minimum and maximum temperature over a period of 24 hours.

domestic species: species living in a human habitat (e.g. house, other type of dwelling).

dose–response relationship: relationship in which a change in amount, intensity or duration of **exposure** is associated with a change (either an increase or a decrease) in risk of a specified outcome. Dose–response relationships are used to determine the probability of a specific outcome or disease, or risk of a disease, by extrapolating from high doses to low doses and from laboratory animals to humans, and using mathematical models that define risk as a function of exposure dose.

dracunculiasis (guinea-worm disease): tropical disease caused by infection with *Dracunculus medinensis*, a parasitic **nematode** that lives in tissue beneath the skin. The disease is transmitted via drinking-water contaminated with the copepod **vector**.

ENSO: see **El Niño/Southern Oscillation**.

echinococcosis: disease caused by infection with *Echinococcus* (a genus of very small tapeworms). Infection is often associated with close contact with dogs, poor sanitation and poor personal hygiene.

ecological study: study in which the analysis of a relationship is based on aggregated or grouped data (such as rates, proportions and means). That is, no data is collected at the level of the individual. Such group-based studies are the only or the best way of studying some relationships. However, caution is needed since errors in inference may result from extrapolating observed relationships concerning the group to the individual level.

ecosystem: mutually interrelated complexes of abiotic components and species communities in a given area, existing as a system, with specific interactions and exchange of matter, energy, and information.

ectoparasite: parasite that lives on the body surface of its **host**, e.g. tick, flea.

El Niño/Southern Oscillation (ENSO): El Niño is the name originally given by local inhabitants to a weak warm ocean current flowing along the coast of Ecuador and Peru. ENSO is an extensive, intense, atmospheric and oceanic phenomenon affecting the tropical Pacific Ocean. It is associated with major anomalies in atmospheric circulation and rainfall patterns. El Niño occurs irregularly, but approximately every four years on average. ENSO events have impacts on fisheries, bird life and mainland weather.

emerging infectious disease: disease that is new in the population or rapidly increasing in **incidence** or expanding in geographical range.

emission scenario: scenario of net **greenhouse gas** and **aerosol precursor** emissions for the next hundred years or more. Emission scenarios provide input for climate models and contribute to the evaluation of future **radiative forcing** of the **atmosphere**. Emission scenarios are not predictions of the future but illustrate the effect of a wide range of economic, demographic, and policy assumptions. The IPCC has defined six emission scenarios (IS92a–IS92f).

encephalitis: inflammation of the brain.

endemic: term applied to describe sustained, relatively stable pattern of infection within a specified population.

enzootic: continued and constant presence of a disease organism in animals other than humans in a geographic area over a long period of time.

epidemic: appearance of abnormally high number of cases of infection in a given population; can also refer to non-infectious diseases (e.g. heart disease) or acute events such as chemical toxicity. (See also **pandemic**.)

epidemiology: study of the distribution and determinants of health-related states or events in specified populations. Epidemiology is the basic quantitative science of public health.

equilibrium climate change experiment: general circulation model (GCM) experiment where a step change is applied to the forcing of a climate model; the model is then allowed to reach a new equilibrium. Such experiments provide information on the difference between the initial and final stages of the model, but not on the time-dependent response.

erythema: reddening of the skin.

eutrophication: the occurrence of high nutrient levels in freshwater and marine **ecosystem**s, usually resulting in excessive plant growth and the death of animal and some plant life due to oxygen deprivation.

evapotranspiration: sum total of water lost from land through physical evaporation and plant transpiration.

exposure: amount of a factor to which a group or individual was exposed; sometimes contrasted with dose, the amount that enters or interacts with the organism. Exposures may be either beneficial or harmful.

extrinsic incubation period: in blood-feeding arthropod vectors, the time between acquisition of the infectious blood meal and the time when the arthropod becomes capable of transmitting the agent. In the case of malaria, the life stages of the plasmodium parasite spent within the female mosquito vector (i.e. outside the human host).

fascioliasis: infestation of the bile ducts and liver with the liver fluke *Fasciola hepatica.* The larval stages of the parasite are transmitted by ingestion of wild watercress. Symptoms include fever, vomiting, abdominal pain; the liver may be extensively damaged.

febrile: relating to or affected with fever.

feedback: modification or control of a process or system via its results or effects.

fibrinogen: soluble blood protein from which the insoluble blood protein fibrin is produced, and which is essential to blood clotting.

free radical: highly reactive chemical molecule that has at least one unpaired electron (e.g. **hydroxyl radical**).

freshwater lens: small shallow aquifer, often the most important source of potable water on small islands.

frontal formation: weather system associated with the meeting of two dissimilar **air mass**es.

GCM: see **general circulation model**.

GHG: see **greenhouse gas**.

GIS: see **geographic information system**.

general circulation model (GCM): computer model that consists of a global, 3-dimensional simulation of the dynamic behaviour of the climate system, based on the physical and chemical properties of its constituents and its interactions with oceanic processes.

geographic information system (GIS): advanced computer-based system for the integrated analysis of different sets of geographically-referenced data.

glacial rebound: natural vertical movement of land caused by melting of large ice sheets following the last glaciation period.

Global Environment Facility: fund managed jointly by the World Bank, UNDP and UNEP, that provides grants for projects and programmes that seek to protect the global environment. It also serves as the interim financial mechanism for the **UN Framework Convention on Climate Change**.

greenhouse gas (GHG): gas that absorbs radiation of specific wavelengths within the infrared spectrum of radiation emitted by Earth's surface and clouds. The effect is a local trapping of part of the absorbed energy and a tendency to warm Earth's surface. Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the primary greenhouse gases in Earth's atmosphere.

haemorrhagic: causing haemorrhage or bleeding.

half-life: period during which the radioactivity of a radioactive substance decreases to half of its original value; similarly applied to the decrease in activity of any unstable active substance with time.

halocarbon: generic term to describe a group of human-made chemicals that contain carbon and members of the halogen family (fluorine, chlorine or bromine). Halocarbons include **chlorofluorocarbon**s and **halon**s, substances that deplete stratospheric **ozone**.

halons: various gaseous compounds of carbon, bromine and other halogens, usually bromofluoromethanes, used to extinguish fires, that contribute to destruction of stratospheric **ozone**.

hantavirus: type of virus; some hantaviruses are pathogenic to humans, causing severe illness. Rodents are the natural **reservoir** of all hantaviruses. Infection in humans occurs via inhalation or ingestion of materials contaminated with rodent excreta, although a tick vector may be involved.

hazard: in **epidemiology**, a factor or **exposure** that may affect health adversely.

heat-budget model: model that evaluates **thermoregulation** by quantifying the heat exchange that occurs between the human body and its environment. The model uses variables such as air temperature, humidity, wind velocity, and short- and long-wave radiation.

heat island effect: local human-induced climate conditions (high temperatures) in urban areas caused by heat absorption in concrete, brick and pavement surfaces, reduction of convective cooling due to presence of tall buildings, and reduced evaporative cooling.

heat load: amount of heat to which a particular object is subjected. In this book, it most often refers to the human body or dwelling.

herd immunity: resistance of a group or community to the invasion and spread of an infectious agent, based on the resistance to infection of a high proportion of individual members of that group or community. The proportion of the population required to be immune varies according to the agent, its transmission characteristics, the distribution of immune and susceptible individuals, and environmental factors.

***Herpes simplex*:** virus that causes inflammation of the skin or mucous membranes, characterized by a small collection of blisters.

heterologous protection: when immunity to one strain of a pathogen does not afford immunity against other strains.

histology: microscopic study of the tissues of organisms.

historical analogue study: study that uses a past event to elucidate factors pertaining to current or future events.

horizontal transmission: any transmission of a disease agent other than that which is transmitted from parent to offspring.

host: organism upon which another lives as a parasite. A host may also be a **vector**, **intermediate host**, or **reservoir**.

household fuel: either gaseous (natural gas), liquid (fuel oil or kerosene) or solid (coal or wood) fuel used for domestic cooking and/or heating.

human papilloma virus (HPV): virus that causes warts, including genital warts. Certain strains are considered to be causative factors in the development of (uterine) cervical cancer and other cancers.

humoral: circulating in the bloodstream. Humoral immunity requires the presence of circulating antibodies.

hydrocarbon: compound of hydrogen and carbon, occurring notably in coal, natural gas and oil.

hydrochlorofluorocarbons (HCFCs): chemicals that contain hydrogen and that are recommended as replacements for stratospheric **ozone**-depleting **chlorofluorocarbons** (CFCs). HCFCs are **greenhouse gas**es and also stratospheric ozone-depleting chemicals, but less so than

CFCs since the hydrogen atoms they contain make it possible for HCFCs to react more readily with **hydroxyl radical**s in the **troposphere**.

hydrofluorocarbons (HFCs): chemicals that contain hydrogen and that are recommended as replacements for stratospheric **ozone**-depleting **chlorofluorocarbons**. HFCs are **greenhouse gas**es and also stratospheric ozone-depleting chemicals, but less so than chlorofluorocarbons because the hydrogen atoms they contain make it possible for HFCs to react more readily with **hydroxyl radical**s in the **troposphere**.

hydrological cycle: movement and circulation of water in the **atmosphere**, on land surfaces, and through the soils and subsurface of rocks. About 97% of the world's water is in the oceans and about 75% of its fresh water takes the form of glaciers and polar ice. Water vapour in the atmosphere condenses and appears as dew or precipitation such as rain, snow or hail. Liquid water and ice and snow evaporate.

hydroxyl radical: one of the most toxic and reactive **free radical** species.

hymenolepiasis: disease caused by infestation with small *Hymenolepis* tapeworms; for example, the rat tapeworm, which may infect humans who come into close contact with rodents.

hypoxia: physiological damage due to lack of oxygen.

ice sheet: a glacier of more than 50 000 km^2 in area forming a continuous cover over a land surface or resting on a continental shelf.

immunosuppression: reduction in effectiveness of an individual's immune system. Local immunosuppression occurs at the site of **exposure** or disturbance (e.g. **contact** or **delayed-type hypersensitivity response**s of the skin). Systemic immunosuppression involves a reduction of the body's immune response at a site distant from the site of exposure.

incidence: the number of cases of illness commencing, or of persons falling ill, during a given time period within a specified population. (See also **prevalence**.)

indices: in epidemiology, these are rating scales; for example, there are many varieties of health status index, or scoring systems, relating to the severity of a disease.

infection rate: proportion of all individuals in a population that is infected with a specific disease agent.

intermediate host: host of a disease agent other than the one in which sexually mature forms of the pathogen occur.

Internet: global computer network providing access to and dissemination of a vast amount of information.

isotherm: line drawn on a map connecting places with the same temperature at a particular time or for a certain period.

ivermectin: drug used to treat **onchocerciasis** and which acts by killing the microfilariae (the immature forms of the parasite).

kwashiorkor: nutritional disorder of infants and young children which occurs when diet is persistently deficient in essential protein. Characteristic features include anaemia, wasting, dependant **oedema** and a fatty liver, and if untreated, death.

Langerhans cells: principal **antigen**-presenting cells in the skin involved in the **contact hypersensitivity response**. Langerhans cells may pick up and transport antigens to T-**lymphocyte**s in the lymphatic system.

leaching: loss of soil elements or applied chemicals as a result of convective–dispersive transport of water through subsurface soils.

legionella: type of bacteria, one species of which causes Legionnaires' disease.

Leishmania: genus of parasitic protozoa, several species of which cause **leishmaniasis** in humans. Transmitted by sandflies, leishmaniasis is common in the tropics and subtropics.

leishmaniasis: infection with a species of ***Leishmania***, resulting in a clinically ill-defined group of diseases. Transmission is by various sandfly species of the genus *Phlebotomus* or *Lutzomyia*.

leptospirosis: bacterial infection of humans by *Leptospira*. Symptoms include high fever, jaundice, severe muscular pains and vomiting. Transmission is associated with contact with infected animals or water contaminated with rat urine. Also known as Weil's disease.

levee: elevated land along a river or stream bank created either naturally, by the deposition of sediment, or artificially, for flood protection.

life table: summarizing technique used by epidemiologists to describe patterns of survival in populations. The survival data used are time-specific and expressed as cumulative probabilities of survival of a group of individuals subject, throughout life, to a particular set of age-specific death rates. The life-table method can be applied to the study not only of death, but also of any defined end-point such as the onset of disease.

life-year: unit used to measure the amount of life lost due to premature death.

longitudinal study (or cohort study): epidemiological study type in which subsets of a defined population can be identified who are, have been, or in the future may be exposed or not exposed, to a factor, or factors, hypothesized to influence the probability of occurrence of a given disease or other outcome. The main feature is observation of large numbers of persons over a long period (usually years) with comparison of **incidence** rates in groups that differ in terms of **exposure** level.

lower atmosphere: see **troposphere**.

lupus erythematosus: an auto-immune illness that affects the skin and internal organs.

lymphatic filariasis: parasitic disease common in tropical and subtropical countries. Long thread-like **nematode** worms cause inflammation and eventual blocking of lymph vessels, causing the surrounding tissue to swell (elephantiasis). The parasites are transmitted to humans by mosquitos (including *Anopheles* spp., *Aedes* spp. and *Culex* spp).

lymphocyte: small white blood cell, one of many present in lymphoid tissues, circulating in blood and lymph and involved in **antigen**-specific immune reactions. Lymphocytes can be subdivided into B-lymphocytes, which produce circulating antibodies, and T-lymphocytes, which are primarily responsible for cell-mediated immunity. T-lymphocytes can be subdivided into: **cytotoxic** T-lymphocytes which bind to and kill foreign cells; helper T-lymphocytes which assist antibody production, and suppressor T-lymphocytes which inhibit this immune response.

MED: see **minimal erythemal dose**.

macular degeneration: degeneration of the retina in the area responsible for central vision, usually associated with old age.

marasmus: severe wasting in infants caused by chronic bacterial or parasitic infection (especially in tropical climates), diarrhoea, repeated vomiting, or other chronic disease. An acute infection may precipitate death.

mathematical model: representation of a system, process or relationship in mathematical form in which equations are used to describe the behaviour of the system or process under study.

meningococcal meningitis: cerebrospinal meningitis or fever.

mesosphere: region of Earth's **atmosphere** above the **stratosphere**.

meta-analysis: process of using statistical methods to combine the results of different independent studies.

Meteosat: weather satellite of the European Space Agency.

microclimate: (i) in climatology: localized climate, incorporating physical processes in the atmospheric boundary layer. The boundary layer is the lowest 100–2000 m of the **atmosphere** and the part of the **troposphere** that is directly influenced by Earth's surface. For example, atmospheric humidity is influenced by vegetation, ambient air temperatures by buildings and roads, etc. (ii) in ecology: climatic conditions in the environmental space occupied by a species, a community of species or an **ecosystem**. For example, on mountain slopes, temperatures experienced by plants differ depending on the direction of the slope. Similarly, in forests, air temperature varies according to canopy cover and height. In many cases, such differentials are crucial for species survival and longevity.

middle atmosphere: see **stratosphere**.

minimal erythemal dose: minimal dose of ultraviolet radiation sufficient to cause **erythema**.

miracidia: embryonic form of a **trematode** worm such as the **schistosome** parasite. After hatching in surface water from eggs excreted by humans, miracidia infect water snails, their **intermediate host**. The parasite multiplies in the snail, and one miracidium produces several hundred **cercaria**e which then infect humans.

mitigation: human intervention to reduce emissions or enhance the sinks of **greenhouse gas**es.

monitoring: performance and analysis of routine measurements aimed at detecting changes in the environment or health status of populations. Not to be confused with **surveillance**, although surveillance techniques may be used in monitoring.

monocultural farming: cultivation over a large area of a single crop species, or of a single variety of a particular species. Monocultures are vulnerable to pest and disease infestation, but uniformity of height, development, etc., in a crop facilitates management, especially harvesting. The ecological wisdom of monocultures is widely debated.

monsoon: season of south-west wind in India and adjacent areas that is characterized by heavy precipitation.

Montreal Protocol, The: international agreement signed in 1987 to limit the production and emission of substances that deplete stratospheric **ozone**. The Parties to the Protocol further agreed to the London and Copenhagen Adjustments and Amendments in 1990 and 1992, respectively, aimed at accelerating the phasing out of ozone-depleting substances by 1 January 1996 (although concessionary delays have been applied to developing countries).

morbidity: rate of occurrence of disease or other health disorder within a population, taking account of the age-specific morbidity rates. Health outcomes include: **chronic disease incidence/prevalence**, rates of hospitalization, primary care consultations, disability-days (e.g. days when absent from work), and prevalence of symptoms.

mortality: rate of occurrence of death within a population within a specified time period; calculation of mortality takes account of age-specific death rates, and can thus yield measures of life expectancy and the extent of premature death.

murine typhus: rickettsial disease transmitted by flea faeces and associated with rodent infestation. Symptoms include fever and a rash. The disease can be fatal.

***Mycobacteria*:** rod-like aerobic bacteria. Some species cause disease in humans, e.g. leprosy (*Mycobacterium leprae*) and tuberculosis (*M. tuberculosis*).

nematode: common name for any roundworm of the phylum Nematoda. Species may be either free-living in sea, fresh water or soil, or parasitic. Parasitic worms may be transmitted between **host**s by the ingestion of eggs, e.g. hookworm, or by the bite of an arthropod **vector**, e.g. the infective agents of lymphatic **filariasis** and **onchocerciasis**.

NO_x: any oxides of nitrogen.

non-linearity: relationship in which, for example, the dose–response relationship is not linear (with or without mathematical transformation). The relationship may entail a **threshold**, step function, or some other complex form (including multiple interactions with other variables).

oedema: swelling caused by the accumulation of fluid in body tissues.

onchocerciasis: also known as river blindness; common in tropical regions of Africa and America; caused by infestation by a filarial worm (especially *Onchocerca volvulus*), transmitted by various species of blackfly, and characterized by subcutaneous nodules and very often blindness.

ozone: form of the element oxygen with three atoms instead of the two that characterize normal oxygen molecules. Ozone (O_3) is an important **greenhouse gas**. The **stratosphere** contains 90% of all the O_3 present in the **atmosphere** that absorbs harmful ultraviolet radiation. In the **troposphere**, O_3 is a secondary air pollutant that has adverse impacts on health.

ozonesonde: instrument which measures **ozone** concentration in the **stratosphere** and is carried there by a balloon.

pH: measure of the acidity or alkalinity of a solution, ranging from 0 (acidic) to 7 (neutral) to 14 (alkaline).

PM_{10}: see **particulates**.

palaeoclimatology: study of past climates based on data from fossils and ice cores.

pandemic: epidemic occurring over a very wide area, crossing international boundaries and usually affecting a large number of people.

particulates: very small solid exhaust particles emitted during the combustion of fossil and **biomass fuel**s. Of greatest concern for health are particulates of less than or equal to 10 μm in diameter, usually designated as PM_{10}. Particulates may consist of a wide variety of substances. Regarding respiratory diseases, particulates composed of acids, metals and polycyclic aromatic **hydrocarbon**s are of greatest concern.

pelagic: a term that describes animals and plants living in the open water of the sea.

person-time: measurement combining person and time, used as a denominator in person-time **incidence** and **mortality** rates. It is the sum of the individual units of time during which the persons in the study population were exposed to the **exposure** of interest. The most frequently used person-time is person-years.

photochemical oxidants: see **secondary air pollutants.**

photoconjunctivitis: acute inflammation of the conjunctiva caused by prolonged **exposure** to intense solar radiation.

photodermatosis: any disease of the skin where the skin lesions are caused by prolonged **exposure** to intense solar radiation.

photokeratitis: acute reversible inflammation of the cornea caused by prolonged **exposure** to intense solar radiation, usually in highly reflective environments. Temporary visual loss associated with ultraviolet radiation reflected from the surface of snow is known as "snow blindness".

photolytic destruction: oxidation as a result of absorption of radiative energy.

photo-oxidation: oxidation of organic chemicals initiated by absorption of photons. Oxidation occurs as a result of absorption of energy at specific wavelengths, usually in the ultraviolet (UV) and visible portions of the electromagnetic energy spectrum. Incident solar radiation has a characteristic spectrum of wavelengths. If a chemical cannot absorb radiative energy at any of these wavelengths, it will not undergo photo-oxidation. In the **stratosphere**, all wavelengths that characterize the wavelengths of the visible portions of the solar energy spectrum are available to induce photo-oxidation. The shorter UV wavelengths are absorbed by stratospheric **ozone**. In the **troposphere**, only those wavelengths that characterize the visible portion of the solar energy spectrum are available to induce photo-oxidation.

photoperiod: the period during every 24 hours when an organism is exposed to daylight.

photosensitize: sensitization of the skin to light, usually due to the action of certain drugs, plants or other substances.

photosynthesis: process by which the energy of sunlight is used by green plants to build up complex substances from carbon dioxide and water.

phytoplankton: the plant component of **plankton**, microscopic drifting or floating organisms found in seas, lakes and rivers. In cool waters, phytoplankton consists mainly of **diatoms**; in warmer waters, **dinoflagellates** form the principal component.

plankton: drifting organisms in oceans, lakes or rivers.

population health: a measure of the health status of populations, proposed in recent years to selectively replace use of the terms *human health*, which is more restrictive, and *public health*, which also encompasses preventive and curative measures and infrastructures.

Precautionary Principle: the adoption of prudence when outcomes are uncertain but potentially serious.

precursor: substance from which the one in question is derived or manufactured.

prevalence: proportion of persons within a given population who are currently affected by a particular disease or risk factor. (See also **incidence**.)

primary air pollutants: air pollutants produced as a result of the combustion of fossil and **biomass fuels**. They include: carbon monoxide, nitrogen oxides, sulfur dioxide, and **particulates**.

primary health care: essential health care made accessible at a cost the relevant country and community can afford, incorporating methods that are practical, scientifically sound and socially acceptable. Each member of a community should have access to primary health care and each member should be involved in its planning, as should related sectors. At the very least it should include: education of the community regarding prevalent health problems and means of alleviating or preventing these health problems; the promotion of adequate supplies of food and proper nutrition; basic sanitation and adequate safe water; maternal and child health care including family planning; the prevention and control of locally-endemic diseases; immunization against the main infectious diseases; appropriate treatment of common diseases and injuries; and the provision of essential drugs.

primary producer: photosynthesizing organism at the bottom of the food web (e.g. **phytoplankton**).

ProMED: Program for Monitoring Emerging Diseases, run by the Federation of American Scientists and sponsored by WHO. It provides a framework, via the **Internet**, for electronic data exchange on outbreaks of emerging diseases.

protocol: plan or set of steps, to be followed in an epidemiological study or in an intervention programme.

pterygium: wing-shaped growth of the conjunctival epithelium.

R_0: see **basic reproduction rate**.

radiative forcing (also known as climate forcing): a simple measure of the importance of a potential climate change mechanism. Radiative forcing is the amount of perturbation of the energy balance of the Earth–atmosphere system (in W/m^2) following, for example, a change in carbon dioxide concentrations or a change in the output of the sun. The climate system responds to radiative forcing so as to re-establish the energy balance. Positive radiative forcing tends to warm Earth's surface and negative radiative forcing tends to cool it. Radiative forcing is normally quoted as a global or annual mean value. A more precise definition of radiative forcing, as used in the IPCC reports, is the amount of perturbation of the energy balance of the surface–**troposphere** system, after allowing for the **stratosphere** to re-adjust to a state of global mean radiative equilibrium.

radical: see **free radical**.

rangeland: unimproved grasslands, shrublands, savannas, hot and cold **deserts**, tundra.

regression analysis: statistical method of determining the "best" mathematical model to describe one variable, the dependant (y) variable, as a function of another variable or a set of variables (multiple regression), the independent (x) variable(s). The most common form is a linear model.

relative humidity: the ratio of the mass of water vapour in a given volume of air to the value for saturated air at the same temperature.

remote sensing: method for observing Earth's surface with instruments, e.g. optical instruments or radar, mounted on satellites or airplanes.

reservoir: refers to any animal, plant, soil or inanimate matter in which a pathogen normally lives and multiplies, and on which it depends primarily for survival; e.g. foxes are a reservoir for rabies. Reservoir **host**s may be asymptomatic.

resurging infectious disease: disease that had been decreasing in a population but which is now rapidly increasing in **incidence** again. Examples include: diphtheria, malaria and cholera. In some cases, resurgence is due to decreases in active control programmes or **surveillance** activities.

retinopathy: any disease of the retina.

rickettsia: group of small non-motile spherical or rod-like parasitic organisms. They resemble bacteria in their cellular structure but, like viruses, cannot reproduce outside the bodies of their **host**s. Their natural hosts are arthropods. Rickettsial diseases that can be transmitted to humans include Rocky Mountain spotted fever and louse-borne **typhus**.

rotaviral diarrhoea: acute non-bacterial gastro-enteritis, caused by rotavirus.

run-off: water from precipitation or irrigation that does not evaporate or seep into soil but flows into rivers, streams or lakes, and that may carry sediment.

Sahel: broad belt of land stretching across Africa immediately south of the Sahara, between the latitudes of 13°N and 17°N. Annual mean temperature is 28–30°C. Annual precipitation averages between 250 and 500 mm. The dry season occurs annually from October to June. Drought is often caused by delayed onset of the rainy season or by the occurrence of a dry spell during the rainy season. The Sahel has a savanna grassland climate but is becoming increasingly subject to desertification.

salinization: accumulation of salt in soils.

***Schistosoma*:** genus of **trematode**s, including the important blood flukes of man and domestic animals, that cause schistosomiasis, using water snails as **intermediate host**s.

schistosome: trematode of genus ***Schistosoma***, five species of which cause the serious tropical disease schistosomiasis.

scombroid fish poisoning: caused by toxin found in the flesh of Scombroidea (e.g. mackerel, sardines, tuna). Poisoning cases occur worldwide, but the disease is acute and self-limiting.

seasonality: seasonal fluctuations in disease transmission or other phenomena.

secondary air pollutants: air pollutants formed by chemical and photochemical reactions of **primary air pollutants** and atmospheric chemicals. **Ozone** is an example of a photochemical oxidant, the large group of oxygenated chemicals formed by atmospheric photochemical reactions.

sediment starvation: prevention (by dams, dikes and **levee**s) of riverine sediment from reaching the coastal zone, resulting in **subsidence** and loss of **wetland**s.

selection bias: in an epidemiological study, an error that is due to systematic differences in characteristics between those who are selected for study and those who are not.

sensitivity: degree to which a system will respond per unit change in climatic conditions (e.g. the extent of change in **ecosystem** composition, structure and functioning following a given change in temperature and precipitation).

sentinel site: specific health facility, usually a general/family practice, that undertakes to maintain **surveillance** and report certain specific predetermined events, such as cases of certain infectious diseases.

serogroup/serotype: identifiable factor or factors in blood serum detected by serological test.

seroprevalence: prevalence of a specified **serotype** in a specified population.

silent wildlife cycle: life cycle of pathogen in which wildlife **host** or hosts do not show evidence of disease.

spectral region: specified range of wavelengths of electromagnetic energy spectrum.
spectrometer: instrument to measure wavelengths in specified **spectral region**.
spirochaete: bacterium with a spiral shape.
sporogony: that part of the sexual reproduction of the malaria parasite that takes place inside the mosquito.
stable malaria: continuous transmission of malaria. (See also **unstable malaria**.)
storm surge: rapid flooding from the sea that accompanies a storm passage.
stratosphere: highly stratified and stable region of the **atmosphere** above the **troposphere** extending from about 10 km to 50 km.
stressor: single condition or agent that contributes to stress of an organism, population or **ecosystem**.
subsidence: sinking of land resulting from downwarping of underlying deposits, compaction of sediments, or removal of subsurface fluids.
suppressor T-lymphocyte: see **lymphocyte**.
surveillance: continuous analysis, interpretation and feedback of systematically collected data for the detection of trends in the occurrence or spread of a disease, based on practical and standardized methods of notification or registration. Sources of data may be related directly to disease or factors influencing disease, and therefore may include: **mortality** and **morbidity** reports based on death certificates, hospital records, **sentinel site**s, or notifications; laboratory diagnoses; outbreak reports; data on vaccine utilization (uptake and side effects); sickness absence records; data on disease determinants such as biological changes in agent, **vector**s or **reservoir**s; data on **susceptibility** to disease, measured by skin testing or serological surveillance (e.g. serum banks).
susceptibility: probability that an individual or population will be affected by an external factor.
sustainable: term used to characterize human activity (e.g. agriculture, forestry) that is undertaken in such a manner that it does not adversely affect environmental conditions (e.g. soil, water quality, climate), and which means that that activity can be repeated in the future.
sylvatic: term used to describe wild animal or plant living in forested areas.
synoptic methods: used to analyse relationships between total atmospheric conditions and the surface environment. Usually expressed in two forms: "**air mass** identification", which assesses the meteorological quality of the entire **atmosphere** (e.g. maritime tropical air mass); and "weather type evaluation", which identifies various weather systems and their impact (e.g. mid-latitude cyclone).
tectonic shift: natural vertical movement of land associated with tectonic deformation of the Earth's crust.
teleconnection: linkage over great distances of seemingly disconnected weather anomalies. Teleconnections are identified through the appearance of geophysical processes, correlated statistically in space and time. The majority of teleconnections that have been described are climate anomalies associated with the **El Niño/Southern Oscillation**.
thermal expansion: expansion of solids, liquids, and gases, associated with an increase in temperature. The volume of the oceans, and thus sea level, varies with seawater density which is dependent upon temperature and salinity. Changes in salinity have minor effects on the global scale, but anticipated increases in global temperature will have significant effects on sea level. Owing to very complex physics, sea level rise by thermal expansion results in significant regional variations and time lags.
thermoregulation: regulation and maintenance of body temperature by various physiological mechanisms.
threshold: abrupt change in the slope or curvature of a dose–response graph.

time-series analysis: statistical method used to describe discrete events that occur randomly, e.g. **mortality** rates for a specified time, as a function of system variables. Such studies examine the concurrent fluctuations in different variables over time.

trace gases: gases that are present in the **atmosphere** in small concentrations, e.g. water vapour, carbon dioxide, methane, nitrous oxide, **ozone** and inert gases. Some trace gases are major **greenhouse gas**es.

trachoma: infectious inflammation of the eye, often associated with lack of water for personal hygiene.

transient climate experiment: general circulation model (GCM) experiment in which the time-dependent response of a climate model is analysed in response to a time-varying change in **radiative forcing**.

transmigration settlement: type of government-run settlement for migrants, found in Indonesia, Brazil, etc., often located on poor soil, in previously forested areas, etc.

trematode: flat worm of the class Trematoda, including the parasitic worms called "flukes". Trematodes that cause disease in humans have intermediate stages in snails, e.g. ***Schistosoma***.

trophic level: step in the transfer of food energy within a chain. There may be several trophic levels within a chain; for example, **primary producer**s, primary consumers (herbivores), secondary consumers (carnivores), and further carnivores. There are rarely more than five levels since the amount of food or energy available at each progressive level is significantly less than that available at the previous level.

troposphere: lowest part of the **atmosphere** (from Earth's surface to about 10 km altitude at mid-latitudes, to about 9 km altitude at high-latitudes and to about 6 km altitude in the tropics) in which clouds and weather phenomena occur. The troposphere is defined as the region in which temperatures generally decrease with height.

trypanosomiasis: parasitic disease caused by protozoan of *Trypanosoma* genus. In the Americas, American trypanosomiasis (Chagas disease) is caused by *T. cruzi*, transmitted by kissing bugs. In Africa, human African trypanosomiasis (sleeping sickness) is caused by *T.brucei rhodesiense* and *T.b. gambiense* and transmitted by tsetse flies.

turnaround time: time required to turn raw data into accessible user-compatible information.

tsunami: very swiftly travelling sea wave that attains great height, caused by an undersea earthquake or similar disturbance.

typhoid: infectious fever usually spread by food, milk or water supplies that have been contaminated with *Salmonella typhi*, either directly by sewage, indirectly by flies, or as a result of poor personal hygiene.

typhus: acute infectious disease characterized by high fever, a skin eruption and severe headache. Typhus is a **rickettsia**l disease, often transmitted by lice.

UN Framework Convention on Climate Change (UNFCCC): convention signed at United Nations Conference on Environment and Development in 1992. Governments that become Parties to the Convention agree to stabilize **greenhouse gas** concentrations in the **atmosphere** at a level that would prevent dangerous **anthropogenic** interference with the climate system.

unstable malaria: haphazard transmission of malaria, occurring only during "favourable" episodes. (See also **stable malaria**.)

upstream assessment: assessment of the causes of a phenomenon.

urbanization: conversion of land from a natural state or managed natural state (such as agriculture) to an urban state.

urocanic acid: chemical present in the skin which is sensitive to ultraviolet radiation and may mediate some of its immunosuppressive effect.

uveal melanoma: melanoma of the pigmented part of the eye.

vector: organism that acts as an essential **intermediate host** or definite **host** for a human pathogen and that plays an active role in its transmission; for example, *Anopheles* species are vectors of malaria. This definition excludes mechanical carriers of infective materials (such as houseflies and cockroaches), strictly passive intermediate hosts (such as the snail hosts of schistosomiasis) and **reservoir** species (such as foxes in the case of rabies).

vector competence: combined effect of all the physiological and ecological factors pertaining to **vector**, **host**, pathogen and environment that determine the relative ability of a vector (relative to another vector) to transmit a specific infective agent resulting in infection.

vectorial capacity: quantitative term used in the study of the transmission dynamics of vector-borne disease, to express the average number of potentially infective bites (inoculations) transmitted by one **vector** species from one infective **host** in one day.

vibrio: bacterium of the *Vibrio* genus. Widely distributed in soil and water. Some species cause disease in man, e.g. *Vibrio cholerae* causes cholera.

vulnerability: extent to which climate change may damage or harm a system; it depends not only on a system's sensitivity, but also on its ability to adapt to new climatic conditions.

water-washed diseases: diseases spread from one person to another due to inadequate supplies of water for personal hygiene. These include infections of the skin and eyes (e.g. **trachoma**) and infections carried by lice, e.g. louse-borne epidemic **typhus**.

weather watch/warning system: system used by health planners and citizens to warn of impending weather conditions that could cause health problems. The systems provide guidance for developing mitigative action.

wet-bulb temperature: temperature measured by a thermometer wrapped in wet gauze or a cloth which is fanned to maximize evaporation. The drier the air, the lower the wet-bulb temperature (due to more evaporation), and the greater the difference between the wet-bulb temperature and air temperature. At 100% **relative humidity**, wet-bulb temperature is equivalent to the air temperature. Wet-bulb temperature is used to determine **relative humidity**.

wetland: land that is periodically flooded, containing emergent vegetation. Wetlands are important **ecosystems** since, among many other functions, they serve as nurseries for fish and detoxify urban waste water.

wild species: species not adapted to life in the urban or domestic environment, and inhabiting their original environment.

xerophthalmia: progressive nutritional disease of the eye caused by vitamin A deficiency and which can lead to blindness.

zoonosis: infectious disease of vertebrate animals, such as rabies, that can be transmitted to humans.

zooplankton: animal component of **plankton**, microscopic drifting or floating organisms found in seas, lakes and rivers.

zootic: pertaining to animals other than humans.

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The sustained health of human populations requires the continued integrity of Earth's natural systems. These systems are now threatened by global climate change and other environmental changes resulting from unsustainable resource use, pollution of air, water and soil, and overcrowding. This book examines the potential human population health hazards of global climate change — defined as a complex of meteorological processes driven by the accumulation of greenhouse gases in the atmosphere. Climate change consequences considered in this text include changes in temperature and precipitation, changes in the frequency of extreme weather events, and sea level rise. The potential human health impacts of increased ultraviolet radiation resulting from stratospheric ozone depletion — although not a component of climate change — are also discussed.

The possible health impacts could occur in a number of ways, via pathways of varying directness and complexity, including disturbance of natural and managed ecosystems. It is anticipated that most of these impacts would be adverse. However, with some exceptions, relatively little research has yet been undertaken that would enable quantitative description of these probable health impacts to be made.

A shorter report appeared as Chapter 18 of Part 2 of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).