8

Human health

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Executive summary

Climate change currently contributes to the global burden of disease and premature deaths (very high confidence).
Human beings are exposed to climate change through changing weather patterns (temperature, precipitation, sea-level rise and more frequent extreme events) and indirectly through changes in water, air and food quality and changes in ecosystems, agriculture, industry and settlements and the economy. At this early stage the effects are small but are projected to progressively increase in all countries and regions. [8.4.1]

Emerging evidence of climate change effects on human health shows that climate change has:

- altered the distribution of some infectious disease vectors (medium confidence) [8.2.8];
- altered the seasonal distribution of some allergenic pollen species (high confidence) [8.2.7];
- increased heatwave-related deaths (medium confidence) [8.2.1].

Projected trends in climate-change-related exposures of importance to human health will:

- increase malnutrition and consequent disorders, including those relating to child growth and development (high confidence) [8.2.3, 8.4.1];
- increase the number of people suffering from death, disease and injury from heatwaves, floods, storms, fires and droughts (high confidence) [8.2.2, 8.4.1];
- continue to change the range of some infectious disease vectors (high confidence) [8.2, 8.4];
- have mixed effects on malaria; in some places the geographical range will contract, elsewhere the geographical range will expand and the transmission season may be changed (very high confidence) [8.4.1.2];
- increase the burden of diarrhoeal diseases (medium confidence) [8.2, 8.4];
- increase cardio-respiratory morbidity and mortality associated with ground-level ozone (high confidence) [8.2.6, 8.4.1.4];
- increase the number of people at risk of dengue (low confidence) [8.2.8, 8.4.1];
- bring some benefits to health, including fewer deaths from cold, although it is expected that these will be outweighed by the negative effects of rising temperatures worldwide, especially in developing countries (high confidence) [8.2.1, 8.4.1].

Adaptive capacity needs to be improved everywhere; impacts of recent hurricanes and heatwaves show that even high-income countries are not well prepared to cope with extreme weather events (high confidence). [8.2.1, 8.2.2]

Adverse health impacts will be greatest in low-income countries. Those at greater risk include, in all countries, the urban poor, the elderly and children, traditional societies, subsistence farmers, and coastal populations (high confidence). [8.1.1, 8.4.2, 8.6.1.3, 8.7]

Economic development is an important component of adaptation, but on its own will not insulate the world's population from disease and injury due to climate change (very high confidence).
Critically important will be the manner in which economic growth occurs, the distribution of the benefits of growth, and factors that directly shape the health of populations, such as education, health care, and public-health infrastructure. [8.3.2]

8.1 Introduction

This chapter describes the observed and projected health impacts of climate change, current and future populations at risk, and the strategies, policies and measures that have been and can be taken to reduce impacts. The chapter reviews the knowledge that has emerged since the Third Assessment Report (TAR) (McMichael et al., 2001). Published research continues to focus on effects in high-income countries, and there remain important gaps in information for the more vulnerable populations in low- and middle-income countries.

8.1.1 State of health in the world

Health includes physical, social and psychological well-being. Population health is a primary goal of sustainable development. Human beings are exposed to climate change through changing weather patterns (for example more intense and frequent extreme events) and indirectly though changes in water, air, food quality and quantity, ecosystems, agriculture, livelihoods and infrastructure (Figure 8.1). These direct and indirect exposures can cause death, disability and suffering. Ill-health increases vulnerability and reduces the capacity of individuals and groups to adapt to climate change. Populations with high rates of disease and debility cope less successfully with stresses of all kinds, including those related to climate change.

In many respects, population health has improved remarkably over the last 50 years. For instance, average life expectancy at birth has increased worldwide since the 1950s (WHO, 2003b, 2004b). However, improvement is not apparent everywhere, and substantial inequalities in health persist within and between countries (Casas-Zamora and Ibrahim, 2004; McMichael et al., 2004; Marmot, 2005; People's Health Movement et al., 2005). In parts of Africa, life expectancy has fallen in the last 20 years, largely as a consequence of HIV/AIDS; in some countries more than 20% of the adult population is infected (UNDP, 2005). Globally, child mortality decreased from 147 to 80 deaths per 1,000 live births from 1970 to 2002 (WHO, 2002b). Reductions were largest in countries in the World Health Organization (WHO) regions of the Eastern Mediterranean, South-East Asia and Latin America. In sixteen countries (fourteen of which are in Africa), current levels of under-five mortality are higher than those observed in 1990 (Anand and Barnighausen, 2004). The Millennium Development Goal (MDG) of reducing under-five mortality rates by two-thirds by 2015 is unlikely to be reached in these countries.

Non-communicable diseases, such as heart disease, diabetes, stroke and cancer, account for nearly half of the global burden of disease (at all ages) and the burden is growing fastest in low- and middle-income countries (Mascie-Taylor and Karim, 2003). Communicable diseases are still a serious threat to public health in many parts of the world (WHO, 2003a) despite immunisation programmes and many other measures that have improved the control of once-common human infections. Almost 2 million deaths a year, mostly in young children, are caused by diarrhoeal diseases and other conditions that are attributable to unsafe water and lack of basic sanitation (Ezzati et al., 2003). Malaria, another common disease whose geographical range may be affected by climate change, causes around 1 million child deaths annually (WHO, 2003b). Worldwide, 840 million people were undernourished in 1998-2000 (FAO, 2002). Progress in overcoming hunger is very uneven. Based on current trends, only Latin America and the Caribbean will achieve the MDG target of halving the proportion of people who are hungry by 2015 (FAO, 2005; UN, 2006a).

8.1.2 Findings from the Third Assessment Report

The main findings of the IPCC TAR (McMichael et al., 2001) were as follows.

- An increase in the frequency or intensity of heatwaves will increase the risk of mortality and morbidity, principally in older age groups and among the urban poor.
- Any regional increases in climate extremes (e.g., storms, floods, cyclones, droughts) associated with climate change would cause deaths and injuries, population displacement, and adverse effects on food production, freshwater availability and quality, and would increase the risks of infectious disease, particularly in low-income countries.
- In some settings, the impacts of climate change may cause social disruption, economic decline, and displacement of populations. The health impacts associated with such socio-economic dislocation and population displacement are substantial.
- Changes in climate, including changes in climate variability, would affect many vector-borne infections. Populations at the margins of the current distribution of diseases might be particularly affected.
- Climate change represents an additional pressure on the world's food supply system and is expected to increase yields at higher latitudes and decrease yields at lower latitudes. This would increase the number of undernourished people in the low-income world, unless there was a major redistribution of food around the world.
- Assuming that current emission levels continue, air quality in many large urban areas will deteriorate. Increases in exposure to ozone and other air pollutants (e.g., particulates) could increase morbidity and mortality.

8.1.3 Key developments since the Third Assessment Report

Overall, research over the last 6 years has provided new evidence to expand the findings of the TAR. Empirical research has further quantified the health effects of heatwaves (see Section 8.2.1). There has been little additional research on the health effects of other extreme weather events. The early effects of climate change on health-relevant exposures have been investigated in the context of changes in air quality and plant and animal phenology (see Chapter 1 and Sections 8.2.7 and 8.2.8). There has been research on a wider range of health issues, including food safety and water-related infections. The contribution made by climate change to the overall burden of disease has been estimated (see Section 8.4.1) (McMichael, 2004). Several countries have conducted health-impact assessments of climate change; either as part of a multi-sectoral study or as a stand-alone project (see Tables 8.1, 8.3 and 8.4). These provide more detailed information on population vulnerability to climate change (see Section 8.4.2). The effect of climate has been studied in the context of other social and environmental determinants of health outcomes (McMichael et al., 2003a; Izmerov et al., 2005). Little advancement has been made in the development of climate–health impact models that project future health effects. Climate change is now an issue of concern for health policy in many countries. Some adaptation measures specific to climate variability have been developed and implemented within and beyond the health sector (see Section 8.6). Many challenges remain for climate- and health-impact and adaptation research. The most important of these is the limited capacity for research and adaptation in low- and middle-income countries.

8.1.4 Methods used and gaps in knowledge

The evidence for the current sensitivity of population health to weather and climate is based on five main types of empirical study:

- health impacts of individual extreme events (e.g., heatwaves, floods, storms, droughts, extreme cold);
- spatial studies where climate is an explanatory variable in the distribution of the disease or the disease vector;
- temporal studies assessing the health effects of interannual climate variability, of short-term (daily, weekly) changes in temperature or rainfall, and of longer-term (decadal) changes in the context of detecting early effects of climate change;
- experimental laboratory and field studies of vector, pathogen, or plant (allergen) biology;
- intervention studies that investigate the effectiveness of public-health measures to protect people from climate hazards.

This assessment of the potential future health impacts of climate change is conducted in the context of:

- limited region-specific projections of changes in exposures of importance to human health;
- the consideration of multiple, interacting and multi-causal health outcomes;
- the difficulty of attributing health outcomes to climate or climate change *per se*;
- the difficulty of generalising health outcomes from one setting to another, when many diseases (such as malaria) have important local transmission dynamics that cannot easily be represented in simple relationships;

- limited inclusion of different developmental scenarios in health projections;
- the difficulty in identifying climate-related thresholds for population health;
- limited understanding of the extent, rate, limiting forces and major drivers of adaptation of human populations to a changing climate.

Table 8.1. *National health impact assessments of climate change published since the TAR.*

Country	Key findings	Adaptation recommendations
Australia (McMichael et al., 2003b)	Increase in heatwave-related deaths; drowning from floods; diarrhoeal disease in indigenous communities; potential change in the geographical range of dengue and malaria; likely increase in environmental refugees from Pacific islands.	Not considered.
Bolivia (Programa Nacional de Cambios Climaticos Componente Salud et al., 2000)	Intensification of malaria and leishmaniasis transmission. Indigenous populations may be most affected by increases in infectious diseases.	Not considered.
Bhutan (National Environment Commission et al., 2006)	Loss of life from frequent flash floods; glacier lake outburst floods; landslides; hunger and malnutrition; spread of vector-borne diseases into higher elevations; loss of water resources; risk of water-borne diseases.	Ensure safe drinking water; regular vector control and vaccination programmes; monitor air and drinking water quality; establishment of emergency medical services.
Canada (Riedel, 2004)	Increase in heatwave-related deaths; increase in air pollution-related diseases; spread of vector- and rodent-borne diseases; increased problems with contamination of both domestic and imported shellfish; increase in allergic disorders; impacts on particular populations in northern Canada.	Monitoring for emerging infectious diseases; emergency management plans; early warning systems; land-use regulations; upgrading water and wastewater treatment facilities; measures for reducing the heat-island effect.
Finland (Hassi and Rytkonen, 2005)	Small increase in heat-related mortality; changes in phenological phases and increased risk of allergic disorders; small reduction in winter mortality.	Awareness-building and training of medical doctors.
Germany (Zebisch et al., 2005)	Observed excess deaths from heatwaves; changing ranges in tick-borne encephalitis; impacts on health care.	Increase information to the population; early warning; emergency planning and cooling of buildings; insurance and reserve funds.
India (Ministry of Environment and Forest and Government of India, 2004)	Increase in communicable diseases. Malaria projected to move to higher latitudes and altitudes in India.	Surveillance systems; vector control measures; public education.
Japan (Koike, 2006)	Increased risk of heat-related emergency visits, Japanese cedar pollen disease patients, food poisoning; and sleep disturbance.	Heat-related emergency visit surveillance.
The Netherlands (Bresser, 2006)	Increase in heat-related mortality, air pollutants; risk of Lyme disease, food poisoning and allergic disorders.	Not considered.
New Zealand (Woodward et al., 2001)	Increases in enteric infections (food poisoning); changes in some allergic conditions; injuries from more intense floods and storms; a small increase in heat-related deaths.	Systems to ensure food quality; information to population and health care providers; flood protection; vector control.
Panama (Autoridad Nacional del Ambiente, 2000)	Increase of vector-borne and other infectious diseases; health problems due to high ozone levels in urban areas; increase in malnutrition.	Not considered.
Portugal (Casimiro and Calheiros, 2002; Calheiros and Casimiro, 2006)	Increase in heat-related deaths and malaria (Tables 8.2, 8.3), food- and water-borne diseases, West Nile fever, Lyme disease and Mediterranean spotted fever; a reduction in leishmaniasis risk in some areas.	Address thermal comfort; education and information as well as early warning for hot periods; and early detection of infectious diseases.
Spain (Moreno, 2005)	Increase in heat-related mortality and air pollutants; potential change of ranges of vector- and rodent-borne diseases.	Awareness-raising; early warning systems for heatwaves; surveillance and monitoring; review of health policies.
Tajikistan (Kaumov and Muchmadeliev, 2002)	Increase in heat-related deaths.	Not considered.
Switzerland (Thommen Dombois and Braun-Fahrlaender, 2004)	Increase of heat-related mortality; changes in zoonoses; increase in cases of tick-borne encephalitis.	Heat information, early warning; greenhouse gas emissions reduction strategies to reduce secondary air pollutants; setting up a working group on climate and health.
United Kingdom (Department of Health and Expert Group on Climate Change and Health in the UK, 2001)	Health impacts of increased flood events; increased risk of heatwave-related mortality; and increased ozone-related exposure.	Awareness-raising.

8.2 Current sensitivity and vulnerability

Systematic reviews of empirical studies provide the best evidence for the relationship between health and weather or climate factors, but such formal reviews are rare. In this section, we assess the current state of knowledge of the associations between weather/climate factors and health outcome(s) for the population(s) concerned, either directly or through multiple pathways, as outlined in Figure 8.1. The figure shows not only the pathways by which health can be affected by climate change, but also shows the concurrent direct-acting and modifying (conditioning) influences of environmental, social and health-system factors.

Published evidence so far indicates that:

- climate change is affecting the seasonality of some allergenic species (see Chapter 1) as well as the seasonal activity and distribution of some disease vectors (see Section 8.2.8);
- climate plays an important role in the seasonal pattern or temporal distribution of malaria, dengue, tick-borne diseases, cholera and some other diarrhoeal diseases (see Sections 8.2.5 and 8.2.8);
- heatwaves and flooding can have severe and long-lasting effects.

8.2.1 Heat and cold health effects

The effects of environmental temperature have been studied in the context of single episodes of sustained extreme temperatures (by definition, heatwaves and cold-waves) and as population responses to the range of ambient temperatures (ecological time-series studies).

8.2.1.1 Heatwaves

Hot days, hot nights and heatwaves have become more frequent (IPCC, 2007a). Heatwaves are associated with marked short-term increases in mortality (Box 8.1). There has been more research on heatwaves and health since the TAR in North America (Basu and Samet, 2002), Europe (Koppe et al., 2004) and East Asia (Qiu et al., 2002; Ando et al., 2004; Choi et al., 2005; Kabuto et al., 2005).

A variable proportion of the deaths occurring during heatwaves are due to short-term mortality displacement (Hajat et al., 2005; Kysely, 2005). Research indicates that this proportion depends on the severity of the heatwave and the health status of the population affected (Hemon and Jougla, 2004; Hajat et al., 2005). The heatwave in 2003 was so severe that short-term mortality displacement contributed very little to the total heatwave mortality (Le Tertre et al., 2006).

Eighteen heatwaves were reported in India between 1980 and 1998, with a heatwave in 1988 affecting ten states and causing 1,300 deaths (De and Mukhopadhyay, 1998; Mohanty and Panda, 2003; De et al., 2004). Heatwaves in Orissa, India, in 1998, 1999 and 2000 caused an estimated 2,000, 91 and 29 deaths, respectively (Mohanty and Panda, 2003) and heatwaves in 2003 in Andhra Pradesh, India, caused more than 3000 deaths (Government of Andhra Pradesh, 2004). Heatwaves in South Asia are associated with high mortality in rural populations, and

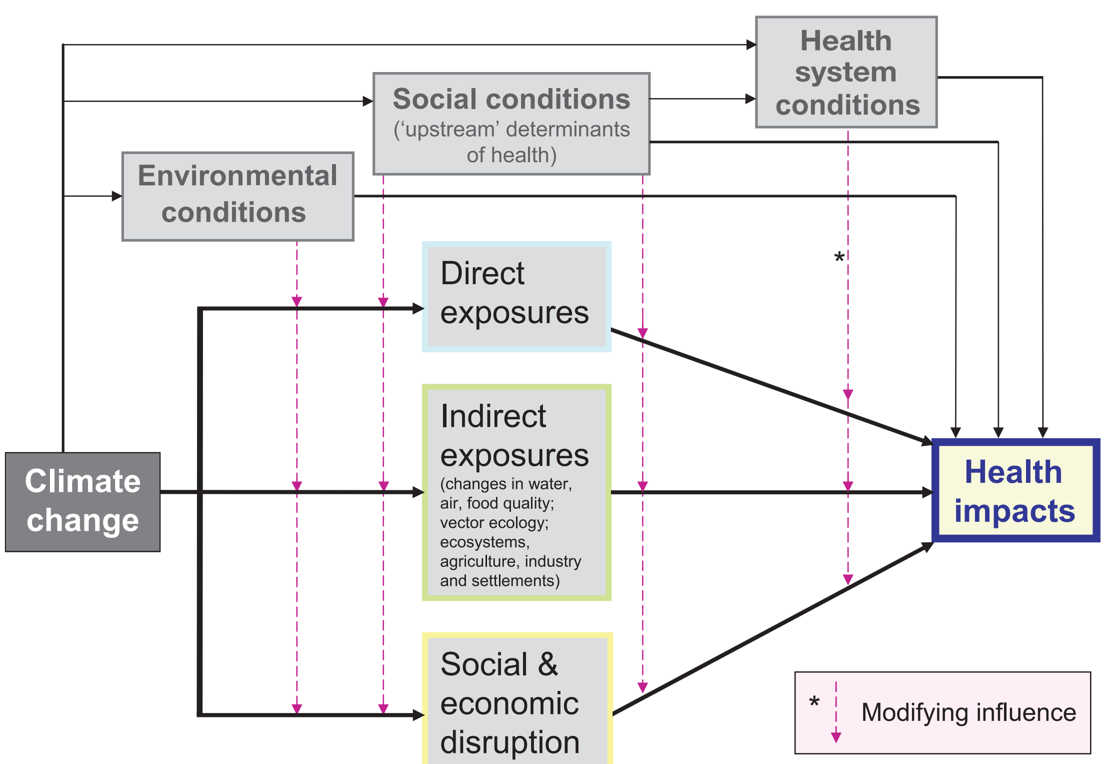

Figure 8.1. *Schematic diagram of pathways by which climate change affects health, and concurrent direct-acting and modifying (conditioning) influences of environmental, social and health-system factors.*

among the elderly and outdoor workers (Chaudhury et al., 2000) (see Section 8.2.9). The mortality figures probably refer to reported deaths from heatstroke and are therefore an underestimate of the total impact of these events.

8.2.1.2 Cold-waves

Cold-waves continue to be a problem in northern latitudes, where very low temperatures can be reached in a few hours and extend over long periods. Accidental cold exposure occurs mainly outdoors, among socially deprived people (alcoholics, the homeless), workers, and the elderly in temperate and cold climates (Ranhoff, 2000). Living in cold environments in polar regions is associated with a range of chronic conditions in the non-indigenous population (Sorogin et al, 1993) as well as with acute risk from frostbite and hypothermia (Hassi et al., 2005). In countries with populations well adapted to cold conditions, cold-

Box 8.1. The European heatwave 2003: impacts and adaptation

In August 2003, a heatwave in France caused more than 14,800 deaths (Figure 8.2). Belgium, the Czech Republic, Germany, Italy, Portugal, Spain, Switzerland, the Netherlands and the UK all reported excess mortality during the heatwave period, with total deaths in the range of 35,000 (Hemon and Jougla, 2004; Martinez-Navarro et al., 2004; Michelozzi et al., 2004; Vandentorren et al., 2004; Conti et al., 2005; Grize et al., 2005; Johnson et al., 2005). In France, around 60% of the heatwave deaths occurred in persons aged 75 and over (Hemon and Jougla, 2004). Other harmful exposures were also caused or exacerbated by the extreme weather, such as outdoor air pollutants (tropospheric ozone and particulate matter) (EEA, 2003), and pollution from forest fires.

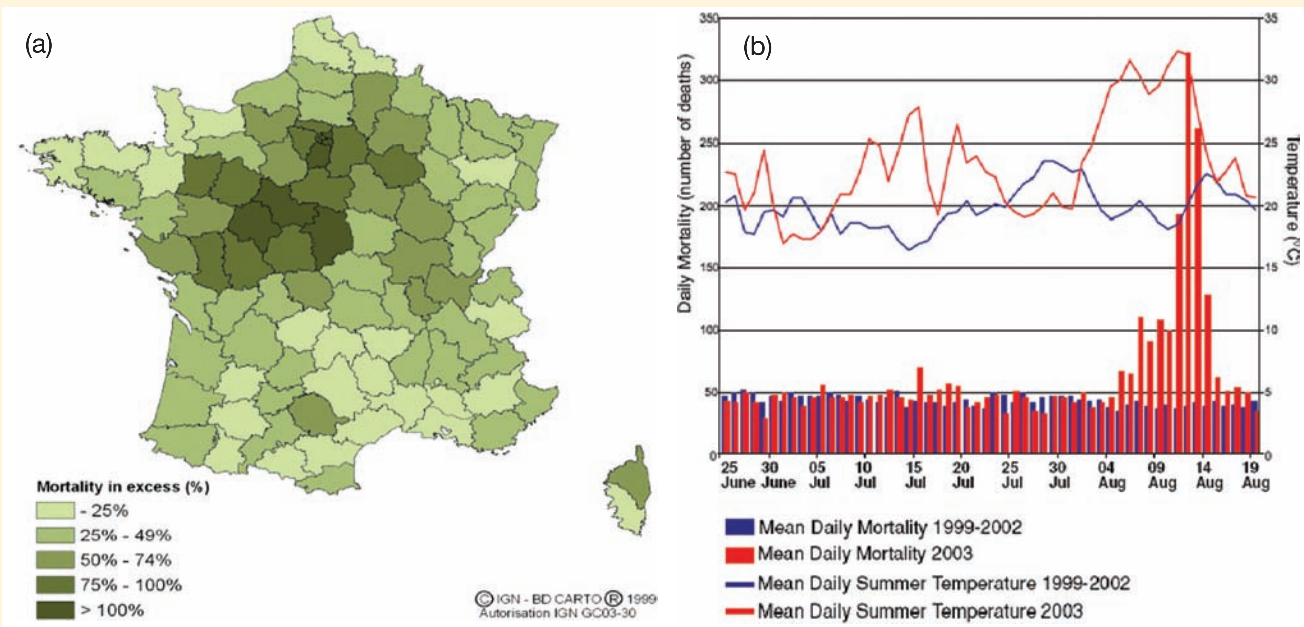

Figure 8.2. *(a) The distribution of excess mortality in France from 1 to 15 August 2003, by region, compared with the previous three years (INVS, 2003); (b) the increase in daily mortality in Paris during the heatwave in early August (Vandentorren and Empereur-Bissonnet, 2005).*

A French parliamentary inquiry concluded that the health impact was 'unforeseen', surveillance for heatwave deaths was inadequate, and the limited public-health response was due to a lack of experts, limited strength of public-health agencies, and poor exchange of information between public organisations (Lagadec, 2004; Sénat, 2004).

In 2004, the French authorities implemented local and national action plans that included heat health-warning systems, health and environmental surveillance, re-evaluation of care of the elderly, and structural improvements to residential institutions (such as adding a cool room) (Laaidi et al., 2004; Michelon et al., 2005). Across Europe, many other governments (local and national) have implemented heat health-prevention plans (Michelozzi et al., 2005; WHO Regional Office for Europe, 2006).

Since the observed higher frequency of heatwaves is likely to have occurred due to human influence on the climate system (Hegerl et al., 2007), the excess deaths of the 2003 heatwave in Europe are likely to be linked to climate change.

waves can still cause substantial increases in mortality if electricity or heating systems fail. Cold-waves also affect health in warmer climates, such as in South-East Asia (EM-DAT, 2006).

8.2.1.3 Estimates of heat and cold effects

Methods for the quantification of heat and cold effects have seen rapid development (Braga et al., 2002; Curriero et al., 2002; Armstrong et al., 2004), including the identification of medical, social, environmental and other factors that modify the temperature–mortality relationship (Basu and Samet, 2002; Koppe et al., 2004). Local factors, such as climate, topography, heat-island magnitude, income, and the proportion of elderly people, are important in determining the underlying temperature–mortality relationship in a population (Curriero et al., 2002; Hajat, 2006). High temperatures contribute to about 0.5 - 2% of annual mortality in older age groups in Europe (Pattenden et al., 2003; Hajat et al., 2006), although large uncertainty remains in quantifying this burden in terms of years of life lost.

The sensitivity of a population to temperature extremes changes over decadal time-scales (Honda et al., 1998). There is some indication that populations in the USA became less sensitive to high temperatures over the period 1964 to 1988 (as measured imprecisely by population- and period-specific thresholds in the mortality response) (Davis et al., 2002, 2003, 2004). Heat-related mortality has declined since the 1970s in South Carolina, USA, and south Finland, but this trend was less clear for the south of England (Donaldson et al., 2003). Cold-related mortality in European populations has also declined since the 1950s (Kunst et al., 1991; Lerchl, 1998; Carson et al., 2006). Cold days, cold nights and frost days have become rarer, but explain only a small part of this reduction in winter mortality; as improved home heating, better general health and improved prevention and treatment of winter infections have played a more significant role (Carson et al., 2006). In general, population sensitivity to cold weather is greater in temperate countries with mild winters, as populations are less well-adapted to cold (Eurowinter Group, 1997; Healy, 2003).

8.2.2 Wind, storms and floods

Floods are low-probability, high-impact events that can overwhelm physical infrastructure, human resilience and social organisation. Floods are the most frequent natural weather disaster (EM-DAT, 2006). Floods result from the interaction of rainfall, surface runoff, evaporation, wind, sea level and local topography. In inland areas, flood regimes vary substantially depending on catchment size, topography and climate. Water management practices, urbanisation, intensified land use and forestry can substantially alter the risks of floods (EEA, 2005). Windstorms are often associated with floods.

Major storm and flood disasters have occurred in the last two decades. In 2003, 130 million people were affected by floods in China (EM-DAT, 2006). In 1999, 30,000 died from storms followed by floods and landslides in Venezuela. In 2000/2001, 1,813 died in floods in Mozambique (IFRC, 2002; Guha-Sapir et al., 2004). Improved structural and non-structural measures, particularly improved warnings, have decreased mortality from floods and storm surges in the last 30 years (EEA, 2005); however, the impact of weather disasters in terms of social and health effects is still considerable and is unequally distributed (see Box 8.2). Flood health impacts range from deaths, injuries, infectious diseases and toxic contamination, to mental health problems (Greenough et al., 2001; Ahern et al., 2005).

In terms of deaths and populations affected, floods and tropical cyclones have the greatest impact in South Asia and Latin America (Guha-Sapir et al., 2004; Schultz et al., 2005). Deaths recorded in disaster databases are from drowning and severe injuries. Deaths from unsafe or unhealthy conditions following the extreme event are also a health consequence, but such information is rarely included in disaster statistics (Combs et al., 1998; Jonkman and Kelman, 2005). Drowning by storm surge is the major killer in coastal storms where there are large numbers of deaths. An assessment of surges in the past 100 years found that major events were confined to a limited number of regions, with many events occurring in the Bay of Bengal, particularly Bangladesh (Nicholls, 2003).

Populations with poor sanitation infrastructure and high burdens of infectious disease often experience increased rates of diarrhoeal diseases after flood events. Increases in cholera (Sur et al., 2000; Gabastou et al., 2002), cryptosporidiosis (Katsumata et al., 1998) and typhoid fever (Vollaard et al., 2004)

Box 8.2. Gender and natural disasters

Men and women are affected differently in all phases of a disaster, from exposure to risk and risk perception; to preparedness behaviour, warning communication and response; physical, psychological, social and economic impacts; emergency response; and ultimately to recovery and reconstruction (Fothergill, 1998). Natural disasters have been shown to result in increased domestic violence against, and post-traumatic stress disorders in, women (Anderson and Manuel, 1994; Garrison et al., 1995; Wilson et al., 1998; Ariyabandu and Wickramasinghe, 2003; Galea et al., 2005). Women make an important contribution to disaster reduction, often informally through participating in disaster management and acting as agents of social change. Their resilience and their networks are critical in household and community recovery (Enarson and Morrow, 1998; Ariyabandu and Wickramasinghe, 2003). After the 1999 Orissa cyclone, most of the relief efforts were targeted at or through women, giving them control over resources. Women received the relief kits, including house-building grants and loans, resulting in improved self-esteem and social status (Briceño, 2002). Similarly, following a disastrous 1992 flood in Pakistan in the Sarghoda district, women were involved in the reconstruction design and were given joint ownership of the homes, promoting their empowerment.

have been reported in low- and middle-income countries. Flood-related increases in diarrhoeal disease have also been reported in India (Mondal et al., 2001), Brazil (Heller et al., 2003) and Bangladesh (Kunii et al., 2002; Schwartz et al., 2006). The floods in Mozambique in 2001 were estimated to have caused over 8,000 additional cases and 447 deaths from diarrhoeal disease in the following months (Cairncross and Alvarinho, 2006).

The risk of infectious disease following flooding in high-income countries is generally low, although increases in respiratory and diarrhoeal diseases have been reported after floods (Miettinen et al., 2001; Reacher et al., 2004; Wade et al., 2004). An important exception was the impact of Hurricanes Katrina and Rita in the USA in 2005, where contamination of water supplies with faecal bacteria led to many cases of diarrhoeal illness and some deaths (CDC, 2005; Manuel, 2006).

Flooding may lead to contamination of waters with dangerous chemicals, heavy metals or other hazardous substances, from storage or from chemicals already in the environment (e.g., pesticides). Chemical contamination following Hurricane Katrina in the USA included oil spills from refineries and storage tanks, pesticides, metals and hazardous waste (Manuel, 2006). Concentrations of most contaminants were within acceptable short-term levels, except for lead and volatile organic compounds (VOCs) in some areas (Pardue et al., 2005). There are also health risks associated with long-term contamination of soil and sediment (Manuel, 2006); however, there is little published evidence demonstrating a causal effect of chemical contamination on the pattern of morbidity and mortality following flooding events (Euripidou and Murray, 2004; Ahern et al., 2005). Increases in population density and accelerating industrial development in areas subject to natural disasters increase the probability of future disasters and the potential for mass human exposure to hazardous materials released during disasters (Young et al., 2004).

There is increasing evidence of the importance of mental disorders as an impact of disasters (Mollica et al., 2004; Ahern et al., 2005). Prolonged impairment resulting from common mental disorders (anxiety and depression) may be considerable. Studies in both low- and high-income countries indicate that the mental-health aspect of flood-related impacts has been insufficiently investigated (Ko et al., 1999; Ohl and Tapsell, 2000; Bokszczanin, 2002; Tapsell et al., 2002; Assanarigkornchai et al., 2004; Norris et al., 2004; North et al., 2004; Ahern et al., 2005; Kohn et al., 2005; Maltais et al., 2005). A systematic review of post-traumatic stress disorder in high-income countries found a small but significant effect following disasters (Galea et al., 2005). There is also evidence of medium- to long-term impacts on behavioural disorders in young children (Durkin et al., 1993; Becht et al., 1998; Bokszczanin, 2000, 2002).

Vulnerability to weather disasters depends on the attributes of the person at risk (including where they live, age, income, education and disability) and on broader social and environmental factors (level of disaster preparedness, health sector responses and environmental degradation) (Blaikie et al., 1994; Menne, 2000; Olmos, 2001; Adger et al., 2005; Few and Matthies, 2006). Poorer communities, particularly slum dwellers, are more likely to live in flood-prone areas. In the USA, lower-income groups were most affected by Hurricane Katrina, and low-income schools had twice the risk of being flooded compared with the reference group (Guidry and Margolis, 2005).

High-density populations in low-lying coastal regions experience a high health burden from weather disasters, such as settlements along the North Sea coast in north-west Europe, the Seychelles, parts of Micronesia, the Gulf Coast of the USA and Mexico, the Nile Delta, the Gulf of Guinea, and the Bay of Bengal (see Chapter 6). Environmentally degraded areas are particularly vulnerable to tropical cyclones and coastal flooding under current climate conditions.

8.2.3 Drought, nutrition and food security

The causal chains through which climate variability and extreme weather influence human nutrition are complex and involve different pathways (regional water scarcity, salinisation of agricultural lands, destruction of crops through flood events, disruption of food logistics through disasters, and increased burden of plant infectious diseases or pests) (see Chapter 5). Both acute and chronic nutritional problems are associated with climate variability and change. The effects of drought on health include deaths, malnutrition (undernutrition, protein-energy malnutrition and/or micronutrient deficiencies), infectious diseases and respiratory diseases (Menne and Bertollini, 2000).

Drought diminishes dietary diversity and reduces overall food consumption, and may therefore lead to micronutrient deficiencies. In Gujarat, India, during a drought in the year 2000, diets were found to be deficient in energy and several vitamins. In this population, serious effects of drought on anthropometric indices may have been prevented by public-health measures (Hari Kumar et al., 2005). A study in southern Africa suggests that HIV/AIDS amplifies the effect of drought on nutrition (Mason et al., 2005). Malnutrition increases the risk both of acquiring and of dying from an infectious disease. A study in Bangladesh found that drought and lack of food were associated with an increased risk of mortality from a diarrhoeal illness (Aziz et al., 1990).

Drought and the consequent loss of livelihoods is also a major trigger for population movements, particularly rural to urban migration. Population displacement can lead to increases in communicable diseases and poor nutritional status resulting from overcrowding, and a lack of safe water, food and shelter (Choudhury and Bhuiya, 1993; Menne and Bertollini, 2000; del Ninno and Lundberg, 2005). Recently, rural to urban migration has been implicated as a driver of HIV transmission (White, 2003; Coffee et al., 2005). Farmers in Australia also appear to be at increased risk of suicide during periods of drought (Nicholls et al., 2005). The range of health impacts associated with a drought event in Brazil are described in Box 8.3.

8.2.3.1 Drought and infectious disease

Countries within the 'Meningitis Belt' in semi-arid sub-Saharan Africa experience the highest endemicity and epidemic frequency of meningococcal meningitis in Africa, although other areas in the Rift Valley, the Great Lakes, and southern Africa are

Box 8.3. Drought in the Amazon

In the dry season of 2005, an intense drought affected the western and central part of the Amazon region, especially Bolivia, Peru and Brazil. In Brazil alone, 280,000 to 300,000 people were affected (see, e.g., Folha, 2006; Socioambiental, 2006). The drought was unusual because it was not caused by an El Niño event, but was linked to a circulation pattern powered by warm seas in the Atlantic – the same phenomenon responsible for the intense Atlantic hurricane season (CPTEC, 2005). There were increased risks to health due to water scarcity, food shortages and smoke from forest fires. Most affected were rural dwellers and riverine traditional subsistence farmers with limited spare resources to mobilise in an emergency. The local and national governments in Brazil provided financial assistance for the provision of safe drinking water, food supplies, medicines and transportation to thousands of people isolated in their communities due to rivers drying up (World Bank, 2005).

also affected. The spatial distribution, intensity and seasonality of meningococcal (epidemic) meningitis appear to be strongly linked to climatic and environmental factors, particularly drought, although the causal mechanism is not clearly understood (Molesworth et al., 2001, 2002a, b, 2003). Climate plays an important part in the interannual variability in transmission, including the timing of the seasonal onset of the disease (Molesworth et al., 2001; Sultan et al., 2005). The geographical distribution of meningitis has expanded in West Africa in recent years, which may be attributable to environmental change driven by both changes in land use and regional climate change (Molesworth et al., 2003).

The transmission of some mosquito-borne diseases is affected by drought events. During droughts, mosquito activity is reduced and, as a consequence, the population of non-immune persons increases. When the drought breaks, there is a much larger proportion of susceptible hosts to become infected, thus potentially increasing transmission (Bouma and Dye, 1997; Woodruff et al., 2002). In other areas, droughts may favour increases in mosquito populations due to reductions in mosquito predators (Chase and Knight, 2003). Other drought-related factors that may result in a short-term increase in the risk for infectious disease outbreaks include stagnation and contamination of drainage canals and small rivers. In the long term, the incidence of mosquito-borne diseases such as malaria decreases because the mosquito vector lacks the necessary humidity and water for breeding. The northern limit of *Plasmodium falciparum* malaria in Africa is the Sahel, where rainfall is an important limiting factor in disease transmission (Ndiaye et al., 2001). Malaria has decreased in association with long-term decreases in annual rainfall in Senegal and Niger (Mouchet et al., 1996; Julvez et al., 1997). Drought events are also associated with dust storms and respiratory health effects (see Section 8.2.6). Droughts are also associated with water scarcity; the risks of water-washed diseases are addressed in Section 8.2.5.

8.2.4 Food safety

Several studies have confirmed and quantified the effects of high temperatures on common forms of food poisoning, such as salmonellosis (D'Souza et al., 2004; Kovats et al., 2004; Fleury et al., 2006). These studies found an approximately linear increase in reported cases with each degree increase in weekly or monthly temperature. Temperature is much less important for the transmission of *Campylobacter* (Kovats et al., 2005; Louis et al., 2005; Tam et al., 2006).

Contact between food and pest species, especially flies, rodents and cockroaches, is also temperature-sensitive. Fly activity is largely driven by temperature rather than by biotic factors (Goulson et al., 2005). In temperate countries, warmer weather and milder winters are likely to increase the abundance of flies and other pest species during the summer months, with the pests appearing earlier in spring.

Harmful algal blooms (HABs) (see Chapter 1, Section 1.3.4.2) produce toxins that can cause human diseases, mainly via consumption of contaminated shellfish. Warmer seas may thus contribute to increased cases of human shellfish and reef-fish poisoning (ciguatera) and poleward expansions of these disease distributions (Kohler and Kohler, 1992; Lehane and Lewis, 2000; Hall et al., 2002; Hunter, 2003; Korenberg, 2004). For example, sea-surface temperatures influence the growth of *Gambierdiscus* spp., which is associated with reports of ciguatera in French Polynesia (Chateau-Degat et al., 2005). No further assessments of the impact of climate change on shellfish poisoning have been carried out since the TAR.

Vibrio parahaemolyticus and *Vibrio vulnificus* are responsible for non-viral infections related to shellfish consumption in the USA, Japan and South-East Asia (Wittmann and Flick, 1995; Tuyet et al., 2002). Abundance is dependent on the salinity and temperature of the coastal water. A large outbreak in 2004 due to the consumption of contaminated oysters (*V. parahaemolyticus*) was linked to atypically high temperatures in Alaskan coastal waters (McLaughlin et al., 2005).

Another example of the implications that climate change can have for food safety is the methylation of mercury and its subsequent uptake by fish and human beings, as observed in the Faroe Islands (Booth and Zeller, 2005; McMichael et al., 2006).

8.2.5 Water and disease

Climate-change-related alterations in rainfall, surface water availability and water quality could affect the burden of water-related diseases (see Chapter 3). Water-related diseases can be classified by route of transmission, thus distinguishing between water-borne (ingested) and water-washed diseases (caused by lack of hygiene). There are four main considerations to take into account when evaluating the relationship between health outcomes and exposure to changes in rainfall, water availability and quality:

- linkages between water availability, household access to improved water, and the health burden due to diarrhoeal diseases;
- the role of extreme rainfall (intense rainfall or drought) in facilitating water-borne outbreaks of diseases through piped water supplies or surface water;
- effects of temperature and runoff on microbiological and chemical contamination of coastal, recreational and surface waters;
- direct effects of temperature on the incidence of diarrhoeal disease.

Access to safe water remains an extremely important global health issue. More than 2 billion people live in the dry regions of the world and suffer disproportionately from malnutrition, infant mortality and diseases related to contaminated or insufficient water (WHO, 2005). A small and unquantified proportion of this burden can be attributed to climate variability or climate extremes. The effect of water scarcity on food availability and malnutrition is discussed in Section 8.2.3, and the effect of rainfall on outbreaks of mosquito-borne and rodent-borne disease is discussed in Section 8.2.8.

Childhood mortality due to diarrhoea in low-income countries, especially in sub-Saharan Africa, remains high despite improvements in care and the use of oral rehydration therapy (Kosek et al., 2003). Children may survive the acute illness but may later die due to persistent diarrhoea or malnutrition. Children in poor rural and urban slum areas are at high risk of diarrhoeal disease mortality and morbidity. Several studies have shown that transmission of enteric pathogens is higher during the rainy season (Nchito et al., 1998; Kang et al., 2001). Drainage and storm water management is important in low-income urban communities, as blocked drains are one of the causes of increased disease transmission (Parkinson and Butler, 2005).

Climate extremes cause both physical and managerial stresses on water supply systems (see Chapters 3 and 7), although well-managed public water supply systems should be able to cope with climate extremes (Nicholls, 2003; Wilby et al., 2005). Reductions in rainfall lead to low river flows, reducing effluent dilution and leading to increased pathogen loading. This could represent an increased challenge to water-treatment plants. During the dry summer of 2003, low flows of rivers in the Netherlands resulted in apparent changes in water quality (Senhorst and Zwolsman, 2005).

Extreme rainfall and runoff events may increase the total microbial load in watercourses and drinking-water reservoirs (Kistemann et al., 2002), although the linkage to cases of human disease is less certain (Schwartz and Levin, 1999; Aramini et al., 2000; Schwartz et al., 2000; Lim et al., 2002). A study in the USA found an association between extreme rainfall events and monthly reports of outbreaks of water-borne disease (Curriero et al., 2001). The seasonal contamination of surface water in early spring in North America and Europe may explain some of the seasonality in sporadic cases of water-borne diseases such as cryptosporidiosis and campylobacteriosis (Clark et al., 2003; Lake et al., 2005). The marked seasonality of cholera outbreaks in the Amazon is associated with low river flow in the dry season (Gerolomo and Penna, 1999), probably due to pathogen concentrations in pools.

Higher temperature was found to be strongly associated with increased episodes of diarrhoeal disease in adults and children in Peru (Checkley et al., 2000; Speelmon et al., 2000; Checkley et al., 2004; Lama et al., 2004). Associations between monthly temperature and diarrhoeal episodes have also been reported in the Pacific islands, Australia and Israel (Singh et al., 2001; McMichael et al., 2003b; Vasilev, 2003).

Although there is evidence that the bimodal seasonal pattern of cholera in Bangladesh is correlated with sea-surface temperatures in the Bay of Bengal and with seasonal plankton abundance (a possible environmental reservoir of the cholera pathogen, *Vibrio cholerae*) (Colwell, 1996; Bouma and Pascual, 2001), winter peaks in disease further inland are not associated with sea-surface temperatures (Bouma and Pascual, 2001). In many countries cholera transmission is primarily associated with poor sanitation. The effect of sea-surface temperatures in cholera transmission has been most studied in the Bay of Bengal (Pascual et al., 2000; Lipp et al., 2002; Rodo et al., 2002; Koelle et al., 2005). In sub-Saharan Africa, cholera outbreaks are often associated with flood events and faecal contamination of the water supplies.

8.2.6 Air quality and disease

Weather at all time scales determines the development, transport, dispersion and deposition of air pollutants, with the passage of fronts, cyclonic and anticyclonic systems and their associated air masses being of particular importance. Air-pollution episodes are often associated with stationary or slowly migrating anticyclonic or high pressure systems, which reduce pollution dispersion and diffusion (Schichtel and Husar, 2001; Rao et al., 2003). Airflow along the flanks of anticyclonic systems can transport ozone precursors, creating the conditions for an ozone event (Lennartson and Schwartz, 1999; Scott and Diab, 2000; Yarnal et al., 2001; Tanner and Law, 2002). Certain weather patterns enhance the development of the urban heat island, the intensity of which may be important for secondary chemical reactions within the urban atmosphere, leading to elevated levels of some pollutants (Morris and Simmonds, 2000; Junk et al., 2003; Jonsson et al., 2004).

8.2.6.1 Ground-level ozone

Ground-level ozone is both naturally occurring and, as the primary constituent of urban smog, is also a secondary pollutant formed through photochemical reactions involving nitrogen oxides and volatile organic compounds in the presence of bright sunshine with high temperatures. In urban areas, transport vehicles are the key sources of nitrogen oxides and volatile organic compounds. Temperature, wind, solar radiation, atmospheric moisture, venting and mixing affect both the emissions of ozone precursors and the production of ozone (Nilsson et al., 2001a, b; Mott et al., 2005). Because ozone formation depends on sunlight, concentrations are typically highest during the summer months, although not all cities have shown seasonality in ozone concentrations (Bates, 2005). Concentrations of ground-level ozone are increasing in most regions (Wu and Chan, 2001; Chen et al., 2004).

Exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis and other respiratory diseases, and with premature mortality (e.g., Mudway and Kelly, 2000; Gryparis et al., 2004; Bell et al., 2005, 2006; Ito et al., 2005; Levy et al., 2005). Outdoor ozone concentrations, activity patterns and housing characteristics, such as the extent of insulation, are the primary determinants of ozone exposure (Suh et al., 2000; Levy et al., 2005). Although a considerable amount is known about the health effects of ozone in Europe and North America, few studies have been conducted in other regions.

8.2.6.2 Effects of weather on concentrations of other air pollutants

Concentrations of air pollutants in general, and fine particulate matter (PM) in particular, may change in response to climate change because their formation depends, in part, on temperature and humidity. Air-pollution concentrations are the result of interactions between variations in the physical and dynamic properties of the atmosphere on time-scales from hours to days, atmospheric circulation features, wind, topography and energy use (McGregor, 1999; Hartley and Robinson, 2000; Pal Arya, 2000). Some air pollutants demonstrate weather-related seasonal cycles (Alvarez et al., 2000; Kassomenos et al., 2001; Hazenkamp-von Arx et al., 2003; Nagendra and Khare, 2003; Eiguren-Fernandez et al., 2004). Some locations, such as Mexico City and Los Angeles, are predisposed to poor air quality because local weather patterns are conducive to chemical reactions leading to the transformation of emissions, and because the topography restricts the dispersion of pollutants (Rappengluck et al., 2000; Kossmann and Sturman, 2004).

Evidence for the health impacts of PM is stronger than that for ozone. PM is known to affect morbidity and mortality (e.g., Ibald-Mulli et al., 2002; Pope et al., 2002; Kappos et al., 2004; Dominici et al., 2006), so increasing concentrations would have significant negative health impacts.

8.2.6.3 Air pollutants from forest fires

In some regions, changes in temperature and precipitation are projected to increase the frequency and severity of fire events (see Chapter 5). Forest and bush fires cause burns, damage from smoke inhalation and other injuries. Large fires are also accompanied by an increased number of patients seeking emergency services (Hoyt and Gerhart, 2004). Toxic gaseous and particulate air pollutants are released into the atmosphere, which can significantly contribute to acute and chronic illnesses of the respiratory system, particularly in children, including pneumonia, upper respiratory diseases, asthma and chronic obstructive pulmonary diseases (WHO, 2002a; Bowman and Johnston, 2005; Moore et al., 2006). For example, the 1997 Indonesia fires increased hospital admissions and mortality from cardiovascular and respiratory diseases, and negatively affected activities of daily living in South-East Asia (Sastry, 2002; Frankenberg et al., 2005; Mott et al., 2005). Pollutants from forest fires can affect air quality for thousands of kilometres (Sapkota et al., 2005).

8.2.6.4 Long-range transport of air pollutants

Changes in wind patterns and increased desertification may increase the long-range transport of air pollutants. Under certain atmospheric circulation conditions, the transport of pollutants, including aerosols, carbon monoxide, ozone, desert dust, mould spores and pesticides, may occur over large distances and over time-scales typically of 4-6 days, which can lead to adverse health impacts (Gangoiti et al., 2001; Stohl et al., 2001; Buchanan et al., 2002; Chan et al., 2002; Martin et al., 2002; Ryall et al., 2002; Ansmann et al., 2003; He et al., 2003; Helmis et al., 2003; Moore et al., 2003; Shinn et al., 2003; Unsworth et al., 2003; Kato et al., 2004; Liang et al., 2004; Tu et al., 2004). Sources of such pollutants include biomass burning, as well as industrial and mobile sources (Murano et al., 2000; Koe et al., 2001; Jaffe et al., 2003, 2004; Moore et al., 2003).

Windblown dust originating in desert regions of Africa, Mongolia, Central Asia and China can affect air quality and population health in remote areas. When compared with non-dust weather conditions, dust can carry large concentrations of respirable particles, trace elements that can affect human health, fungal spores and bacteria (Claiborn et al., 2000; Fan et al., 2002; Shinn et al., 2003; Cook et al., 2005; Prospero et al., 2005; Xie et al., 2005; Kellogg and Griffin, 2006). However, recent studies have not found statistically significant associations between Asian dust storms and hospital admissions in Canada and Taiwan (Chen and Tang, 2005; Yang et al., 2005a; Bennett et al., 2006). Evidence suggests that local mortality, particularly from cardiovascular and respiratory diseases, is increased in the days following a dust storm (Kwon et al., 2002; Chen et al., 2004).

8.2.7 Aeroallergens and disease

Climate change has caused an earlier onset of the spring pollen season in the Northern Hemisphere (see Chapter 1, Section 1.3.7.4; D'Amato et al., 2002; Weber, 2002; Beggs, 2004). It is reasonable to conclude that allergenic diseases caused by pollen, such as allergic rhinitis, have experienced some concomitant change in seasonality (Emberlin et al., 2002; Burr et al., 2003). There is limited evidence that the length of the pollen season has also increased for some species. Although there are suggestions that the abundance of a few species of air-borne pollens has increased due to climate change, it is unclear whether the allergenic content of these pollen types has changed (pollen content remaining the same or increasing would imply increased exposure) (Huynen and Menne, 2003; Beggs and Bambrick, 2005). Few studies show patterns of increasing exposure for allergenic mould spores or bacteria (Corden et al., 2003; Harrison et al., 2005). Changes in the spatial distribution of natural vegetation, such as the introduction of new aeroallergens into an area, increases sensitisation (Voltolini et al., 2000; Asero, 2002). The introduction of new invasive plant species with highly allergenic pollen, in particular ragweed (*Ambrosia artemisiifolia*), presents important health risks; ragweed is spreading in several parts of the world (Rybnicek and Jaeger, 2001; Huynen and Menne, 2003; Taramarcaz et al., 2005; Cecchi et al., 2006). Several laboratory studies show that increasing CO_2 concentrations and temperatures increase ragweed pollen production and prolong the ragweed pollen season (Wan et al., 2002; Wayne et al., 2002; Singer et al., 2005; Ziska et al., 2005; Rogers et al., 2006a) and increase some plant metabolites that can affect human health (Ziska et al., 2005; Mohan et al., 2006).

8.2.8 Vector-borne, rodent-borne and other infectious diseases

Vector-borne diseases (VBD) are infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies and blackflies. VBDs are among the most well-studied of the diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors. There is some evidence of climate-change-related shifts in the distribution of tick vectors of disease, of some (non-malarial) mosquito vectors in Europe and North America, and in the phenology of bird reservoirs of pathogens (see Chapter 1 and Box 8.4).

Northern or altitudinal shifts in tick distribution have been observed in Sweden (Lindgren and Talleklint, 2000; Lindgren and Gustafson, 2001) and Canada (Barker and Lindsay, 2000), and altitudinal shifts have been observed in the Czech Republic (Daniel et al., 2004). Geographical changes in tick-borne infections have been observed in Denmark (Skarphedinsson et al., 2005). Climate change alone is unlikely to explain recent increases in the incidence of tick-borne diseases in Europe or North America. There is considerable spatial heterogeneity in the degree of increase of tick-borne encephalitis, for example, within regions of Europe likely to have experienced similar levels of climate change (Patz, 2002; Randolph, 2004; Sumilo et al., 2006). Other explanations cannot be ruled out, e.g., human impacts on the landscape, increasing both the habitat and wildlife hosts of ticks, and changes in human behaviour that may increase human contact with infected ticks (Randolph, 2001).

In north-eastern North America, there is evidence of recent micro-evolutionary (genetic) responses of the mosquito species *Wyeomyia smithii* to increased average land surface temperatures and earlier arrival of spring in the past two decades (Bradshaw and Holzapfel, 2001). Although not a vector of human disease, this species is closely related to important arbovirus vector species that may be undergoing similar evolutionary changes.

Cutaneous leishmaniasis has been reported in dogs (reservoir hosts) further north in Europe, although the possibility of previous under-reporting cannot be excluded (Lindgren and Naucke, 2006). Changes in the geographical distribution of the sandfly vector have been reported in southern Europe (Aransay et al., 2004; Afonso et al., 2005). However, no study has investigated the causes of these changes. The re-emergence of kala-azar (visceral leishmaniasis) in cities of the semi-arid Brazilian north-eastern region in the early 1980s and 1990s was caused by rural–urban migration of subsistence farmers who had lost their crops due to prolonged droughts (Franke et al., 2002; Confalonieri, 2003).

8.2.8.1 Dengue

Dengue is the world's most important vector-borne viral disease. Several studies have reported associations between spatial (Hales et al., 2002), temporal (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001) or spatiotemporal patterns of dengue and climate (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001; Cazelles et al., 2005). However, these reported associations are not entirely consistent, possibly reflecting the complexity of climatic effects on transmission, and/or the presence of competing factors (Cummings, 2004). While high rainfall or high temperature can lead to an increase in transmission, studies have shown that drought can also be a cause if household water storage increases the number of suitable mosquito breeding sites (Pontes et al., 2000; Depradine and Lovell, 2004; Guang et al., 2005).

Climate-based (temperature, rainfall, cloud cover) density maps of the main dengue vector *Stegomyia* (previously called

Box 8.4. Climate change, migratory birds and infectious diseases

Several species of wild birds can act as biological or mechanical carriers of human pathogens as well as of vectors of infectious agents (Olsen et al., 1995; Klich et al., 1996; Gylfe et al., 2000; Friend et al., 2001; Pereira et al., 2001; Broman et al., 2002; Moore et al., 2002; Niskanen et al., 2003; Rappole and Hubalek, 2003; Reed et al., 2003; Fallacara et al., 2004; Hubalek, 2004; Krauss et al., 2004). Many of these birds are migratory species that seasonally fly long distances through different continents (de Graaf and Rappole, 1995; Webster et al., 2002b). Climate change has been implicated in changes in the migratory and reproductive phenology (advancement in breeding and migration dates) of several bird species, their abundance and population dynamics, as well as a northward expansion of their geographical range in Europe (Sillett et al., 2000; Barbraud and Weimerskirch, 2001; Parmesan and Yohe, 2003; Brommer, 2004; Visser et al., 2004; Both and Visser, 2005). Two possible consequences of these phenological changes in birds to the dispersion of pathogens and their vectors are:

1. shifts in the geographical distribution of the vectors and pathogens due to altered distributions or changed migratory patterns of bird populations;
2. changes in the life cycles of bird-associated pathogens due to the mistiming between bird breeding and the breeding of vectors, such as mosquitoes. One example is the transmission of St. Louis encephalitis virus, which depends on meteorological triggers (e.g., precipitation) to bring the pathogen, vector and host (nestlings) cycles into synchrony, allowing an overlap that initiates and facilitates the cycling necessary for virus amplification between mosquitoes and wild birds (Day, 2001).

Aedes) *aegypti* are a good match with the observed disease distribution (Hopp and Foley, 2003). The model of vector abundance has good agreement with the distribution of reported cases of dengue in Colombia, Haiti, Honduras, Indonesia, Thailand and Vietnam (Hopp and Foley, 2003). Approximately one-third of the world's population lives in regions where the climate is suitable for dengue transmission (Hales et al., 2002; Rogers et al., 2006b).

8.2.8.2 Malaria

The spatial distribution, intensity of transmission, and seasonality of malaria is influenced by climate in sub-Saharan Africa; socio-economic development has had only limited impact on curtailing disease distribution (Hay et al., 2002a; Craig et al., 2004).

Rainfall can be a limiting factor for mosquito populations and there is some evidence of reductions in transmission associated with decadal decreases in rainfall. Interannual malaria variability is climate-related in specific eco-epidemiological zones (Julvez et al., 1992; Ndiaye et al., 2001; Singh and Sharma, 2002; Bouma, 2003; Thomson et al., 2005). A systematic review of studies of the El Niño-Southern Oscillation (ENSO) and malaria concluded that the impact of El Niño on the risk of malaria epidemics is well established in parts of southern Asia and South America (Kovats et al., 2003). Evidence of the predictability of unusually high or low malaria anomalies from both sea-surface temperature (Thomson et al., 2005) and multi-model ensemble seasonal climate forecasts in Botswana (Thomson et al., 2006) supports the practical and routine use of seasonal forecasts for malaria control in southern Africa (DaSilva et al., 2004).

The effects of observed climate change on the geographical distribution of malaria and its transmission intensity in highland regions remains controversial. Analyses of time-series data in some sites in East Africa indicate that malaria incidence has increased in the apparent absence of climate trends (Hay et al., 2002a, b; Shanks et al., 2002). The proposed driving forces behind the malaria resurgence include drug resistance of the malaria parasite and a decrease in vector control activities. However, the validity of this conclusion has been questioned because it may have resulted from inappropriate use of the climatic data (Patz, 2002). Analysis of updated temperature data for these regions has found a significant warming trend since the end of the 1970s, with the magnitude of the change affecting transmission potential (Pascual et al., 2006). In southern Africa, long-term trends for malaria were not significantly associated with climate, although seasonal changes in case numbers were significantly associated with a number of climatic variables (Craig et al., 2004). Drug resistance and HIV infection were associated with long-term malaria trends in the same area (Craig et al., 2004).

A number of further studies have reported associations between interannual variability in temperature and malaria transmission in the African highlands. An analysis of de-trended time-series malaria data in Madagascar indicated that minimum temperature at the start of the transmission season, corresponding to the months when the human–vector contact is greatest, accounts for most of the variability between years (Bouma, 2003). In highland areas of Kenya, malaria admissions have been associated with rainfall and unusually high maximum temperatures 3-4 months previously (Githeko and Ndegwa, 2001). An analysis of malaria morbidity data for the period from the late 1980s until the early 1990s from 50 sites across Ethiopia found that epidemics were associated with high minimum temperatures in the preceding months (Abeku et al., 2003). An analysis of data from seven highland sites in East Africa reported that short-term climate variability played a more important role than long-term trends in initiating malaria epidemics (Zhou et al., 2004, 2005), although the method used to test this hypothesis has been challenged (Hay et al., 2005b).

There is no clear evidence that malaria has been affected by climate change in South America (Benitez et al., 2004) (see Chapter 1) or in continental regions of the Russian Federation (Semenov et al., 2002). The attribution of changes in human diseases to climate change must first take into account the considerable changes in reporting, surveillance, disease control measures, population changes, and other factors such as land-use change (Kovats et al., 2001; Rogers and Randolph, 2006).

Despite the known causal links between climate and malaria transmission dynamics, there is still much uncertainty about the potential impact of climate change on malaria at local and global scales (see also Section 8.4.1) because of the paucity of concurrent detailed historical observations of climate and malaria, the complexity of malaria disease dynamics, and the importance of non-climatic factors, including socio-economic development, immunity and drug resistance, in determining infection and infection outcomes. Given the large populations living in highland areas of East Africa, the limitations of the analyses conducted, and the significant health risks of epidemic malaria, further research is warranted.

8.2.8.3 Other infectious diseases

Recent investigations of plague foci in North America and Asia with respect to the relationships between climatic variables, human disease cases (Enscore et al., 2002) and animal reservoirs (Stapp et al., 2004; Stenseth, 2006) have suggested that temporal variations in plague risk can be estimated by monitoring key climatic variables.

There is good evidence that diseases transmitted by rodents sometimes increase during heavy rainfall and flooding because of altered patterns of human–pathogen–rodent contact. There have been reports of flood-associated outbreaks of leptospirosis (Weil's diseases) from a wide range of countries in Central and South America and South Asia (Ko et al., 1999; Vanasco et al., 2002; Confalonieri, 2003; Ahern et al., 2005). Risk factors for leptospirosis for peri-urban populations in low-income countries include flooding of open sewers and streets during the rainy season (Sarkar et al., 2002).

Cases of hantavirus pulmonary syndrome (HPS) were first reported in Central America (Panama) in 2000, and a suggested cause was the increase in peri-domestic rodents following increased rainfall and flooding in surrounding areas (Bayard et al., 2000), although this requires further investigation. There are climate-related differences in hantavirus dynamics between northern and central Europe (Vapalahti et al., 2003; Pejoch and Kriz, 2006).

The distribution and emergence of other infectious diseases have been affected by weather and climate variability. ENSO-driven bush fires and drought, as well as land-use and land-cover changes, have caused extensive changes in the habitat of some bat species that are the natural reservoirs for the Nipah virus. The bats were driven to farms to find food (fruits), consequently shedding virus and causing an epidemic in Malaysia and neighbouring countries (Chua et al., 2000).

The distribution of schistosomiasis, a water-related parasitic disease with aquatic snails as intermediate hosts, may be affected by climatic factors. In one area of Brazil, the length of the dry season and human population density were the most important factors limiting schistosomiasis distribution and abundance (Bavia et al., 1999). Over a larger area, there was an inverse association between prevalence rates and the length of the dry period (Bavia et al., 2001). Recent studies in China indicate that the increased incidence of schistosomiasis over the past decade may in part reflect the recent warming trend. The critical 'freeze line' limits the survival of the intermediate host (*Oncomelania* water snails) and hence limits the transmission of the parasite *Schistosoma japonicum*. The freeze line has moved northwards, putting an additional 20.7 million people at risk of schistosomiasis (Yang et al., 2005b).

8.2.9 Occupational health

Changes in climate have implications for occupational health and safety. Heat stress due to high temperature and humidity is an occupational hazard that can lead to death or chronic ill-health from the after-effects of heatstroke (Wyndham, 1965; Afanas'eva et al., 1997; Adelakun et al., 1999). Both outdoor and indoor workers are at risk of heatstroke (Leithead and Lind, 1964; Samarasinghe, 2001; Shanks and Papworth, 2001). The occupations most at risk of heatstroke, based on data from the USA, include construction and agriculture/forestry/fishing work (Adelakun et al., 1999; Krake et al., 2003). Acclimatisation in tropical environments does not eliminate the risk, as evidenced by the occurrence of heatstroke in metal workers in Bangladesh (Ahasan et al., 1999) and rickshaw pullers in South Asia (OCHA, 2003). Several of the heatstroke deaths reported in the 2003 and 2006 heatwaves in Paris were associated with occupational exposure (Senat, 2004)

Hot working environments are not just a question of comfort, but a concern for health protection and the ability to perform work tasks. Working in hot environments increases the risk of diminished ability to carry out physical tasks (Kerslake, 1972), diminishes mental task ability (Ramsey, 1995), increases accident risk (Ramsey et al., 1983) and, if prolonged, may lead to heat exhaustion or heatstroke (Hales and Richards, 1987) (see Section 8.5).

8.2.10 Ultraviolet radiation and health

Solar ultraviolet radiation (UVR) exposure causes a range of health impacts. Globally, excessive solar UVR exposure has caused the loss of approximately 1.5 million disability-adjusted life years (DALYs) (0.1% of the total global burden of disease) and 60,000 premature deaths in the year 2000. The greatest burdens result from UVR-induced cortical cataracts, cutaneous malignant melanoma, and sunburn (although the latter estimates are highly uncertain due to the paucity of data) (Prüss-Üstün et al., 2006). UVR exposure may weaken the immune response to certain vaccinations, which would reduce their effectiveness. However, there are also important health benefits: exposure to radiation in the ultraviolet B frequency band is required for the production of vitamin D in the body. Lack of sun exposure may lead to osteomalacia (rickets) and other disorders caused by vitamin D deficiencies.

Climate change will alter human exposure to UVR exposure in several ways, although the balance of effects is difficult to predict and will vary depending on location and present exposure to UVR. Greenhouse-induced cooling of the stratosphere is expected to prolong the effect of ozone-depleting gases, which will increase levels of UVR reaching some parts of the Earth's surface (Beggs, 2005; IPCC/TEAP, 2005). Climate change will alter the distribution of clouds which will, in turn, affect UVR levels at the surface. Higher ambient temperatures will influence clothing choices and time spent outdoors, potentially increasing UVR exposure in some regions and decreasing it in others. If immune function is impaired and vaccine efficacy is reduced, the effects of climate-related shifts in infections may be greater than would occur in the absence of high UVR levels (Zwander, 2002; de Gruijl et al., 2003; Holick, 2004; Gallagher and Lee, 2006; Samanek et al., 2006).

8.3 Assumptions about future trends

The impacts of developmental, climatic and environmental scenarios on population health are important for health-system planning processes. Also, future trends in health are relevant to climate change because the health of populations is an important element of adaptive capacity.

8.3.1 Health in scenarios

The use of scenarios to explore future effects of climate change on population health is at an early stage of development (see Section 8.4.1). Published scenarios describe possible future pathways based on observed trends or explicit storylines, and have been developed for a variety of purposes, including the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), the IPCC Special Report on Emissions Scenarios (SRES, Nakićenović and Swart, 2000), GEO3 (UNEP, 2002) and the World Water Report (United Nations World Water Assessment Programme, 2003; Ebi and Gamble, 2005). Examples of the many possible futures that have been described include possible changes in the patterns of infectious diseases, medical technology, and health and social inequalities (Olshansky et al., 1998; IPCC, 2000; Martens and Hilderink, 2001; Martens and Huynen, 2003). Infectious diseases could become more prominent if public-health systems unravel, or if new pathogens arise that are resistant to our current methods of disease control, leading to falling life expectancies and reduced economic productivity (Barrett et al., 1998). An age of expanded medical technology could result from increased economic growth and improvements in technology, which may to some extent offset deteriorations in the physical and social environment, but at the risk of widening current health inequalities (Martens and Hilderink, 2001). Alternatively, an age of sustained health could result from more wide-ranging investment in social and medical services, leading to a reduction in the incidence of disease, benefiting most segments of the population.

Common to these scenarios is a view that major risks to health will remain unless the poorest countries share in the growth and development experienced by richer parts of the world. It is envisaged also that greater mobility and more rapid spread of ideas and technology worldwide will bring a mix of positive and negative effects on health, and that a deliberate focus on sustainability will be required to reduce the impacts of human activity on climate, water and food resources (Goklany, 2002).

8.3.2 Future vulnerability to climate change

The health of populations is an important element of adaptive capacity. Where there is a heavy burden of disease and disability, the effects of climate change are likely to be more severe than otherwise. For example, in Africa and Asia the future course of the HIV/AIDS epidemic will significantly influence how well populations can cope with challenges such as the spread of climate-related infections (vector- or water-borne), food shortages, and increased frequency of storms, floods and droughts (Dixon et al., 2002).

The total number of people at risk, the age structure of the population, and the density of settlement are important variables in any projections of the effects of climate change. Many populations will age appreciably in the next 50 years. This is relevant to climate change because the elderly are more vulnerable than younger age groups to injury resulting from weather extremes such as heatwaves, storms and floods. It is assumed (with a high degree of confidence) that over the course of the 21st century the population will grow substantially in many of the poorest countries of the world, while numbers will remain much the same, or decline, in the high-income countries. The world population will increase from its current 6.4 billion to somewhat below 9 billion by the middle of the century (Lutz et al., 2000), but regional patterns will vary widely. For example, the population density of Europe is projected to fall from 32 to 27 people/km^2, while that of Africa could rise from 26 to 60 people/km^2 (Cohen, 2003). Currently, 70% of all episodes of clinical *Plasmodium falciparum* malaria worldwide occur in Africa, and that fraction will rise substantially in the future (World Bank et al., 2004). Also relevant to considerations of the impacts of climate change is urbanisation, because the effects of higher temperatures and altered patterns of rainfall are strongly modified by the local environment. For instance, during hot weather, temperatures tend to be higher in built-up areas, due to the urban heat-island effect. Almost all the growth in population in the next 50 years is expected to occur in cities (and in particular, cities in poor countries) (Cohen, 2003). These trends in population dominate calculations of the possible consequences of climate change. These are two examples: projections of the numbers of people affected by coastal flooding and the spread of malaria are more sensitive to assumptions about future population trajectories than to the choice of climate-change model (Nicholls, 2004; van Lieshout et al., 2004).

For much of the world's population, the ability to lead a healthy life is limited by the direct and indirect effects of poverty (World Bank et al., 2004). Although the percentage of people living on less than US$1/day has decreased in Asia and Latin America since 1990, in the sub-Saharan region 46% of the population is now living on less than US$1/day and little improvement is expected in the short and medium term. Poverty levels in Europe and Central Asia show few signs of improvement (World Bank, 2004; World Bank et al., 2004). Economic growth in the richest regions has outstripped advances in other parts of the world, meaning that global disparities in income have increased in the last 20 years (UNEP and WCMC, 2002).

In the future, vulnerability to climate will depend not only on the extent of socio-economic change, but also on how evenly the benefits and costs are distributed, and the manner in which change occurs (McKee and Suhrcke, 2005). Economic growth is double-sided. Growth entails social change, and while this change may be wealth-creating, it may also, in the short term at least, cause significant social stress and environmental damage. Rapid urbanisation (leading to plummeting population health) in western Europe in the 19th century, and extensive land clearance (causing widespread ecological damage) in South America and South-East Asia in the 20th century, are two examples of negative consequences of rapid economic growth (Szreter, 2004). Social disorder, conflict, and lack of effective civic institutions will also increase vulnerability to health risks resulting from climate change.

Health services provide a buffer against the hazards of climate variability and change. For instance, access to cheap, effective anti-malarials, insecticide-treated bed nets and indoor spray programmes will be important for future trends in malaria. Emergency medical services have a role (although not a predominant one) in limiting excess mortality due to heatwaves and other extreme climate events.

There are other determinants of vulnerability that relate to particular threats, or particular settings. Heatwaves, for example, are exacerbated by the urban heat-island effect, so that impacts of high temperatures will be modified by the size and design of future cities (Meehl and Tebaldi, 2004). The consequences of changes in food production due to climate change will depend on access to international markets and the conditions of trade. If these conditions exclude or penalise poor countries, then the risks of disease and ill-health due to malnutrition will be much higher than if a more inclusive economic order is achieved. Changes in land-use practices for the production of biofuels in place of grain and other food crops will have benefits for greenhouse gas emissions reductions, but the way in which the fuels are burnt is also important (see Section 8.7.1).

8.4 Key future impacts and vulnerabilities

The impacts of climate change have been projected for a limited range of health determinants and outcomes for which the epidemiologic evidence base is well developed. The studies reviewed in Section 8.4.1 used quantitative and qualitative approaches to project the incidence and geographical range of health outcomes under different climate and socio-economic scenarios. Section 8.4.2 assesses the possible consequences of climate-change-related health impacts on particularly vulnerable populations and regions in the next few decades

Overall, climate change is projected to have some health benefits, including reduced cold-related mortality, reductions in some pollutant-related mortality, and restricted distribution of diseases where temperatures or rainfall exceed upper thresholds for vectors or parasites. However, the balance of impacts will be overwhelmingly negative (see Section 8.7). Most projections suggest modest changes in the burden of climate-sensitive health outcomes over the next few decades, with larger increases beginning mid-century. The balance of positive and negative health impacts will vary from one location to another and will alter over time as temperatures continue to rise.

8.4.1 Projections of climate-change-related health impacts

Projections of climate-change-related health impacts use different approaches to classify the risk of climate-sensitive health determinants and outcomes. For malaria and dengue, results from projections are commonly presented as maps of potential shifts in distribution. Health-impact models are typically based on climatic constraints on the development of the vector and/or parasite, and include limited population projections and non-climate assumptions. However, there are important differences between disease risk (on the basis of climatic and entomological considerations) and experienced morbidity and mortality. Although large portions of Europe and the USA may be at potential risk for malaria based on the distribution of competent disease vectors, locally acquired cases have been virtually eliminated, in part due to vector- and disease-control activities. Projections for other health outcomes often estimate populations-at-risk or person-months at risk.

Economic scenarios cannot be directly related to disease burdens because the relationships between gross domestic product (GDP) and burdens of climate-sensitive diseases are confounded by social, environmental and climate factors (Arnell et al., 2004; van Lieshout et al., 2004; Pitcher et al., 2007). The assumption that increasing per capita income will improve population health ignores the fact that health is determined by factors other than income alone; that good population health in itself is a critical input into economic growth and long-term economic development; and that persistent challenges to development are a reality in many countries, with continuing high burdens from relatively easy-to-control diseases (Goklany, 2002; Pitcher et al., 2007).

8.4.1.1 Global burden of disease study

The World Health Organization conducted a regional and global comparative risk assessment to quantify the amount of premature morbidity and mortality due to a range of risk factors, including climate change, and to estimate the benefit of interventions to remove or reduce these risk factors. In the year 2000, climate change is estimated to have caused the loss of over 150,000 lives and 5,500,000 DALYs (0.3% of deaths and 0.4% of DALYs, respectively) (Campbell-Lendrum et al., 2003; Ezzati et al., 2004; McMichael, 2004). The assessment also addressed how much of the future burden of climate change could be avoided by stabilising greenhouse gas emissions (Campbell-Lendrum et al., 2003). The health outcomes included were chosen based on known sensitivity to climate variation, predicted future importance, and availability of quantitative global models (or the feasibility of constructing them):

- episodes of diarrhoeal disease,
- cases of *Plasmodium falciparum* malaria,
- fatal accidental injuries in coastal floods and inland floods/landslides,
- the non-availability of recommended daily calorie intake (as an indicator for the prevalence of malnutrition).

Limited adjustments for adaptation were included in the estimates.

The projected relative risks attributable to climate change in 2030 vary by health outcome and region, and are largely negative, with most of the projected disease burden being due to increases in diarrhoeal disease and malnutrition, primarily in low-income populations already experiencing a large burden of disease (Campbell-Lendrum et al., 2003; McMichael, 2004). Absolute disease burdens depend on assumptions of population growth, future baseline disease incidence and the extent of adaptation.

The analyses suggest that climate change will bring some health benefits, such as lower cold-related mortality and greater crop yields in temperate zones, but these benefits will be greatly outweighed by increased rates of other diseases, particularly infectious diseases and malnutrition in low-income countries. A proportional increase in cardiovascular disease mortality attributable to climate extremes is projected in tropical regions, and a small benefit in temperate regions. Climate change is projected to increase the burden of diarrhoeal diseases in low-income regions by approximately 2 to 5% in 2020. Countries with an annual GDP per capita of US$6,000 or more are assumed to have no additional risk of diarrhoea. Coastal flooding is projected to result in a large proportional mortality increase under unmitigated emissions; however, this is applied to a low burden of disease, so the aggregate impact is small. The relative risk is projected to increase as much in high- as in low-income countries. Large changes are projected in the risk of *Plasmodium falciparum* malaria in countries at the edge of the current distribution, with relative changes being much smaller in areas that are currently highly endemic for malaria (McMichael et al., 2004; Haines et al., 2006).

8.4.1.2 Malaria, dengue and other infectious diseases

Studies published since the TAR support previous projections that climate change could alter the incidence and geographical range of malaria. The magnitude of the projected effect may be smaller than that reported in the TAR, partly because of advances in categorising risk. There is greater confidence in projected changes in the geographical range of vectors than in changes in disease incidence because of uncertainties about trends in factors other than climate that influence human cases and deaths, including the status of the public-health infrastructure.

Table 8.2 summarises studies that project the impact of climate change on the incidence and geographical range of malaria, dengue fever and other infectious diseases. Models with incomplete parameterisation of biological relationships between temperature, vector and parasite often over-emphasise relative changes in risk, even when the absolute risk is small. Several modelling studies used the SRES climate scenarios, a few applied population scenarios, and none incorporated economic scenarios. Few studies incorporate adequate assumptions about adaptive capacity. The main approaches used are inclusion of current 'control capacity' in the observed climate–health function (Rogers and Randolph, 2000; Hales et al., 2002) and categorisation of the model output by adaptive capacity, thereby separating the effects of climate change from the effects of improvements in public health (van Lieshout et al., 2004).

Malaria is a complex disease to model and all published models have limited parameterisation of some of the key factors that influence the geographical range and intensity of malaria transmission. Given this limitation, models project that, particularly in Africa, climate change will be associated with geographical expansions of the areas suitable for stable *Plasmodium falciparum* malaria in some regions and with contractions in other regions (Tanser et al., 2003; Thomas et al., 2004; van Lieshout et al., 2004; Ebi et al., 2005). Projections also suggest that some regions will experience a longer season of transmission. This may be as important as geographical expansion for the attributable disease burden. Although an increase in months per year of transmission does not directly translate into an increase in malaria burden (Reiter et al., 2004), it would have important implications for vector control.

Few models project the impact of climate change on malaria outside Africa. An assessment in Portugal projected an increase in the number of days per year suitable for malaria transmission; however, the risk of actual transmission would be low or negligible if infected vectors are not present (Casimiro et al., 2006). Some central Asian areas are projected to be at increased risk of malaria, and areas in Central America and around the Amazon are projected to experience reductions in transmission due to decreases in rainfall (van Lieshout et al., 2004). An assessment in India projected shifts in the geographical range and duration of the transmission window for *Plasmodium falciparum* and *P. vivax* malaria (Bhattacharya et al., 2006). An assessment in Australia based on climatic suitability for the main anopheline vectors projected a likely southward expansion of habitat, although the future risk of endemicity would remain low due to the capacity to respond (McMichael et al., 2003a).

Dengue is an important climate-sensitive disease that is largely confined to urban areas. Expansions of vector species that can carry dengue are projected for parts of Australia and New Zealand (Hales et al., 2002; Woodruff, 2005). An empirical model based on vapour pressure projected increases in latitudinal distribution. It was estimated that, in the 2080s, 5-6 billion people would be at risk of dengue as a result of climate change and population increase, compared with 3.5 billion people if the climate remained unchanged (Hales et al., 2002).

The projected impacts of climate change on other vector-borne diseases, including tick-borne encephalitis and Lyme disease, are discussed in the chapters dealing with Europe (Chapter 12) and North America (Chapter 14).

8.4.1.3 Heat- and cold-related mortality

Evidence of the relationship between high ambient temperature and mortality has strengthened since the TAR, with increasing emphasis on the health impacts of heatwaves. Table 8.3 summarises projections of the impact of climate change on heat- and cold-related mortality. There is a lack of information on the effects of thermal stress on mortality outside the industrialised countries.

Reductions in cold-related deaths due to climate change are projected to be greater than increases in heat-related deaths in the UK (Donaldson et al., 2001). However, projections of cold-related deaths, and the potential for decreasing their numbers due to warmer winters, can be overestimated unless they take into account the effects of influenza and season (Armstrong et al., 2004).

Heat-related morbidity and mortality is projected to increase. Heat exposures vary widely, and current studies do not quantify the years of life lost due to high temperatures. Estimates of the burden of heat-related mortality attributable to climate change are reduced, but not eliminated, when assumptions about acclimatisation and adaptation are included in models. On the other hand, increasing numbers of older adults in the population will increase the proportion of the population at risk because a decreased ability to thermo-regulate is a normal part of the aging process. Overall, the health burden could be relatively small for moderate heatwaves in temperate countries, because deaths occur primarily in susceptible persons. Additional research is needed to understand how the balance of heat-related and cold-related mortality could change under different socio-economic scenarios and climate projections.

8.4.1.4 Urban air quality

Background levels of ground-level ozone have risen since pre-industrial times because of increasing emissions of methane, carbon monoxide and nitrogen oxides; this trend is expected to continue over the next 50 years (Fusco and Logan, 2003; Prather et al., 2003). Changes in concentrations of ground-level ozone driven by scenarios of future emissions and/or weather patterns have been projected for Europe and North America (Stevenson et al., 2000; Derwent et al., 2001; Johnson et al., 2001; Taha, 2001; Hogrefe et al., 2004). Future emissions are, of course, uncertain, and depend on assumptions of population growth, economic development, regulatory actions and energy use (Syri et al., 2002; Webster et al., 2002a). Assuming no change in the

Table 8.2. *Projected impacts of climate change on malaria, dengue fever and other infectious diseases.*

Health effect	Metric	Model	Climate scenario, with time slices	Temperature increase and baseline	Population projections and other assumptions	Main results	Reference
Malaria, global and regional	Population at risk in areas where climate conditions are suitable for malaria transmission	Biological model, calibrated from laboratory and field data, for *falciparum* malaria	HadCM3, driven by SRES A1FI, A2, B1, and B2 scenarios. 2020s, 2050s, 2080s		SRES population scenarios; current malaria control status used as an indicator of adaptive capacity	Estimates of the additional population at risk for >1 month transmission range from >220 million (A1FI) to >400 million (A2) when climate and population growth are included. The global estimates are severely reduced if transmission risk for more than 3 consecutive months per year is considered, with a net reduction in the global population at risk under the A2 and B1 scenarios.	van Lieshout et al., 2004
Malaria, Africa	Person-months at risk for stable *falciparum* transmission	MARA/ARMA[a] model of climate suitability for stable *falciparum* transmission	HadCM3, driven by SRES A1FI, A2a, and B1 scenarios. 2020s, 2050s, 2080s	1.1 to 1.3°C in 2020s; 1.9 to 3.0°C in 2050s; 2.6 to 5.3°C in 2080s	Estimates based on 1995 population	By 2100, 16 to 28% increase in person-months of exposure across all scenarios, including a 5 to 7% increase in (mainly altitudinal) distribution, with limited latitudinal expansion. Countries with large areas that are close to the climatic thresholds for transmission show large potential increases across all scenarios.	Tanser et al., 2003
Malaria, Africa	Map of climate suitability for stable *falciparum* transmission [minimum 4 months suitable per year]	MARA/ARMA[a] model of climate suitability for stable *falciparum* transmission	HadCM2 ensemble mean with medium-high emissions. 2020s, 2050s, 2080s		Climate factors only (monthly mean and minimum temperature, and monthly precipitation)	Decreased transmission in 2020s in south-east Africa. By 2050s and 2080s, localised increases in highland and upland areas, and decreases around Sahel and south central Africa.	Thomas et al., 2004
Malaria, Zimbabwe, Africa	Climate suitability for transmission	MARA/ARMA[a] model of climate suitability for stable *falciparum* transmission	16 climate projections from COSMIC. Climate sensitivities of 1.4 and 4.5°C; equivalent CO_2 of 350 and 750 ppm 2100		None	Highlands become more suitable for transmission. The lowlands and regions with low precipitation show varying degrees of change, depending on climate sensitivity, emissions scenario and GCM.	Ebi et al., 2005
Malaria, Britain	Probability of malaria transmission	Statistical multivariate regression, based on historic distributions, land cover, agricultural factors and climate determinants	1 to 2.5°C average temperature increase 2050s	1 to 2.5°C average temperature increase	None. No changes in land cover or agricultural factors.	Increase in risk of local malaria transmission of 8 to 15%; highly unlikely that indigenous malaria will be re-established.	Kuhn et al., 2002
Malaria, Portugal	Percentage days per year with favourable temperature for disease transmission	Transmission risk based on published thresholds	PROMES for 2040s and HadRM2 for 2090s	Average annual temperature increase of 3.3°C in 2040s and 5.8°C in 2090s, compared with 1981-1990 and 2006-2036, respectively	Some assumptions about vector distribution and/or introduction	Significant increase in the number of days suitable for survival of malaria vectors; however, if no infected vectors are present, then the risk is very low for *vivax* and negligible for *falciparum* malaria.	Casimiro and Calheiros, 2002
Malaria, Australia	Geographical area suitable/unsuitable for maintenance of vector	Empirical-statistical model (CLIMEX) based on current distribution, relative abundance, and seasonal phenology of main malaria vector	CSIROMk2 and ECHAM4 driven by SRES B1, A1B, and A1FI emissions scenarios 2020, 2050	0.4 to 2.0°C annual average temperature increase in the 2030s, and 1.0 to 6.0°C in the 2070s, relative to 1990 (CSIRO)	Assumes adaptive capacity; used Australian population projections	'Malaria receptive zone' expands southward to include some regional towns by 2050s. Absolute risk of reintroduction very low.	McMichael et al., 2003b

[a] The Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique Project

Table 8.2. *Continued.*

Health effect	Metric	Model	Climate scenario, with time slices	Temperature increase and baseline	Population projections and other assumptions	Main results	Reference
Malaria, India, all states	Climate suitability for *falciparum* and *vivax* malaria transmission	Temperature transmission windows based on observed associations between temperature and malaria cases	HadRM2 driven by IS92a emissions scenario	2 to 4°C increase compared with current climate	None	By 2050s, geographical range projected to shift away from central regions towards south-western and northern states. The duration of the transmission window is likely to widen in northern and western states and shorten in southern states.	Bhattacharya et al., 2006
Dengue, global	Population at risk	Statistical model based on vapour pressure. Baseline number of people at risk is 1.5 billion.	ECHAM4, HadCM2, CCSR/NIES, CGCMA2, and CGCMA1 driven by IS92a emissions scenarios		Population growth based on region-specific projections	By 2085, with both population growth and climate change, global population at risk 5 to 6 billion; with climate change only, global population at risk 3.5 billion.	Hales et al., 2002
Dengue, New Zealand	Map of vector 'hotspots'; dengue currently not present in New Zealand	Threshold model based on rainfall and temperature	DARLAM GCM driven by A2 and B2 emissions scenarios 2050, 2100		None	Potential risk of dengue outbreaks in some regions under the current climate. Climate change projected to increase risk of dengue in more regions.	de Wet et al., 2001
Dengue, Australia	Map of regions climatically suitable for dengue transmission	Empirical model (Hales et al., 2002)	CSIROMk2, ECHAM4, and GFDL driven by high (A2) and low (B2) emissions scenarios and a stabilisation scenario at 450 ppm 2100	1.8 to 2.8°C global average temperature increase compared with 1961-1990	None	Regions climatically suitable increase southwards; size of suitable area varies by scenario. Under the high-emissions scenario, regions as far south as Sydney could become climatically suitable.	Woodruff et al., 2005
Lyme disease, Canada	Geographical range and abundance of Lyme disease vector *Ixodes scapularis*	Statistical model based on observed relationships; tick-abundance model	CGCM2 and HADCM2 driven by SRES A2 and B2 emissions scenarios 2020s, 2050s, 2080s		None	Northward expansion of approximately 200 km by 2020s under both scenarios, and approximately 1000 km by 2080s under A2. Under the A2 scenario, tick abundance increases 30 to 100% by 2020s and 2- to 4-fold by 2080s. Seasonality shifts.	Ogden et al., 2006
Tick-borne encephalitis, Europe	Geographical range	Statistical model based on present-day distribution	HadCM2 driven by low, medium-low, medium-high, and high degrees of change (not further defined) 2020s, 2050s, 2080s	3.45°C increase in mean temperature in 2050s under high scenario, baseline not defined	None	From low to high degrees of climate change, tick-borne encephalitis is pushed further northeast of its present range, only moving westward into southern Scandinavia. Only under the low and medium-low scenarios does tick-borne encephalitis remain in central and eastern Europe by the 2050s.	Randolph and Rogers, 2000
Diarrhoeal disease, global, 14 world regions	Diarrhoea incidence (mortality)	Statistical model, derived from cross-sectional study, including annual average temperature, water supply and sanitation coverage, and GDP per capita	SRES A1B, A2, B1 and B2 emissions scenarios 2025, 2055		SRES population growth	Results vary by region and scenario. Generally, diarrhoeal disease increases with temperature increase.	Hijioka et al., 2002
Diarrhoeal disease, Aboriginal community, central Australia (Alice Springs)	Hospital admissions in children aged under 10	Exposure–response relationship based on published studies	CSIROMk2 and ECHAM4 driven by SRES B1, A1B and A1FI emissions scenarios 2020, 2050	0.4 to 2.0°C annual average temperature increase in the 2030s, and 1.0 to 6.0°C in the 2070s, relative to 1990 (CSIRO)	None	Compared with baseline, no significant increase by 2020 and an annual increase of 5 to 18% by 2050.	McMichael et al., 2003b
Food poisoning, England and Wales	Notified cases of food poisoning (non-specific)	Statistical model, based on observed relationship with temperature	UKCIP scenarios 2020s, 2050s, 2080s	0.57 to 1.38°C in 2020s; 0.89 to 2.44°C in 2050s; 1.13 to 3.47°C in 2080s compared with 1961-1990 baseline	None	For +1, +2 and +3°C temperature increases, absolute increases of approximately 4,000, 9,000, and 14,000 notified cases of food poisoning	Department of Health and Expert Group on Climate Change and Health in the UK, 2001

Table 8.3. *Projected impacts of climate change on heat- and cold-related mortality.*

Area	Health effect	Model	Climate scenario, time slices	Temperature increase and baseline	Population projections and other assumptions	Main results	Reference
UK	Heat- and cold-related mortality	Empirical-statistical model derived from observed mortality	UKCIP scenarios 2020s, 2050s, 2080s	0.57 to 1.38°C in 2020s; 0.89 to 2.44°C in 2050s; 1.13 to 3.47°C in 2080s compared with 1961-1990 baseline	Population held constant at 1996. No acclimatisation assumed.	Annual heat-related deaths increase from 798 in 1990s to 2,793 in 2050s and 3,519 in the 2080s under the medium-high scenario. Annual cold-related deaths decrease from 80,313 in 1990s to 60,021 in 2050s and 51,243 in 2080s under the medium-high scenario.	Donaldson et al., 2001
Germany, Baden-Wuertemberg	Heat- and cold-related mortality	Thermo-physiological model combined with conceptual model for adaptation	ECHAM4-OPYC3 driven by SRES A1B emissions scenario. 2001-2055 compared with 1951-2001		Population growth and aging and short-term adaptation and acclimatisation.	About a 20% increase in heat-related mortality. Increase not likely to be compensated by reductions in cold-related mortality.	Koppe, 2005
Lisbon, Portugal	Heat-related mortality	Empirical-statistical model derived from observed summer mortality	PROMES and HadRM2 2020s, 2050s, 2080s	1.4 to 1.8°C in 2020s; 2.8 to 3.5°C in 2050s; 5.6 to 7.1°C in 2080s, compared with 1968-1998 baseline	SRES population scenarios. Assumes some acclimatisation.	Increase in heat-related mortality from baseline of 5.4 to 6 deaths/100,000 to 5.8 to 15.1 deaths/100,000 by the 2020s, 7.3 to 35.9 deaths/100,000 by the 2050s, 19.5 to 248.4 deaths/100,000 by the 2080s	Dessai, 2003
Four cities in California, USA (Los Angeles, Sacramento, Fresno, Shasta Dam)	Annual number of heatwave days, length of heatwave season, and heat-related mortality	Empirical-statistical model derived from observed summer mortality	PCM and HadCM3 driven by SRES B1 and A1FI emissions scenarios 2030s, 2080s	1.35 to 2.0°C in 2030s; 2.3 to 5.8°C in 2080s compared with 1961-1990 baseline	SRES population scenarios. Assumes some adaptation.	Increase in annual number of days classified as heatwave conditions. By 2080s, in Los Angeles, number of heatwave days increases 4-fold under B1 and 6 to 8-fold under A1FI. Annual number of heat-related deaths in Los Angeles increases from about 165 in the 1990s to 319 to 1,182 under different scenarios.	Hayhoe, 2004
Australian capital cities (Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth, Sydney)	Heat-related mortality in people older than 65 years	Empirical-statistical model, derived from observed daily mortality	CSIROMk2, ECHAM4, and HADCM2 driven by SRES A2 and B2 emissions scenarios and a stabilisation scenario at 450 ppm 2100	0.8 to 5.5°C increase in annual maximum temperature in the capital cities, compared with 1961-1990 baseline	Population growth and population aging. No acclimatisation.	Increase in temperature-attributable death rates from 82/100,000 across all cities under the current climate to 246/100,000 in 2100; death rates decreased with implementation of policies to mitigate GHG.	McMichael et al., 2003b

emissions of ozone precursors, the extent to which climate change affects the frequency of future 'ozone episodes' will depend on the occurrence of the required meteorological conditions (Jones and Davies, 2000; Sousounis et al., 2002; Hogrefe et al., 2004; Laurila et al., 2004; Mickley et al., 2004). Table 8.4 summarises projections of future morbidity and mortality based on current exposure–mortality relationships applied to projected ozone concentrations. An increase in ozone concentrations will affect the ability of regions to achieve air-quality targets. There are no projections for cities in low- or middle-income countries, despite the heavier pollution burdens in these populations.

There are few models of the impact of climate change on other pollutants. These tend to emphasise the role of local abatement strategies in determining the future levels of, primarily, particulate matter, and tend to project the probability of air-quality standards being exceeded instead of absolute concentrations (Jensen et al., 2001; Guttikunda et al., 2003; Hicks, 2003; Slanina and Zhang, 2004); the results vary by region. The severity and duration of summertime regional air pollution episodes (as diagnosed by tracking combustion carbon monoxide and black carbon) are projected to increase in the north-eastern and Midwest USA by 2045-2052 because of climate-change-induced decreases in the frequency of surface cyclones (Mickley et al., 2004). A UK study projected that climate change will result in a large decrease in days with high particulate concentrations due to changes in meteorological conditions (Anderson et al., 2001). Because transboundary

Table 8.4. *Projected impacts of climate change on ozone-related health effects.*

Area	Health effect	Model	Climate scenario, time slices	Temperature increase and baseline	Population projections and other assumptions	Main results	Reference
New York metropolitan region, USA	Ozone-related deaths by county	Concentration response function from published epidemiological literature. Gridded ozone concentrations from CMAQ (Community Multiscale Air Quality model).	GISS driven by SRES A2 emissions scenario downscaled using MM5 2050s	1.6 to 3.2°C in 2050s compared with 1990s	Population and age structure held constant at year 2000. Assumes no change from United States Environmental Protection Agency (USEPA) 1996 national emissions inventory and A2-consistent increases in NO_x and VOCs by 2050s.	A2 climate only: 4.5% increase in ozone-related deaths. Ozone elevated in all counties. A2 climate and precursors: 4.4% increase in ozone-related deaths. (Ozone not elevated in all areas due to NO_x interactions.)	Knowlton et al., 2004
50 cities, eastern USA	Ozone-related hospitalis-ations and deaths	Concentration response function from published epidemiological literature. Gridded ozone concentrations from CMAQ.	GISS driven by SRES A2 emissions scenario downscaled using MM5 2050s	1.6 to 3.2°C in 2050s compared with 1990s	Population and age structure held constant at year 2000. Assumes no change from USEPA 1996 national emissions inventory and A2-consistent increases in NO_x and VOCs by 2050s.	Maximum ozone concentrations increased for all cities, with the largest increases in cities with currently higher concentrations. 68% increase in average number of days/summer exceeding the 8-hour regulatory standard, resulting in 0.11 to 0.27% increase in non-accidental mortality and an average 0.31% increase in cardiovascular disease mortality.	Bell et al., 2007
England and Wales	Exceedance days (ozone, particulates, NO_x)	Statistical, based on meteorological factors for high-pollutant days (temperature, wind speed).	UKCIP scenarios 2020s, 2050s, 2080s	0.57 to 1.38°C in 2020s; 0.89 to 2.44°C in 2050s; 1.13 to 3.47°C in 2080s compared with 1961-1990 baseline	Emissions held constant.	Over all time periods, large decreases in days with high particulates and SO_2, small decrease in other pollutants except ozone, which may increase.	Anderson et al., 2001

transport of pollutants plays a significant role in determining local to regional air quality (Holloway et al., 2003; Bergin et al., 2005), changing patterns of atmospheric circulation at the hemispheric to global level are likely to be just as important as regional patterns for future local air quality (Takemura et al., 2001; Langmann et al., 2003).

8.4.2 Vulnerable populations and regions

Human health vulnerability to climate change was assessed based on a range of scientific evidence, including the current burdens of climate-sensitive health determinants and outcomes, projected climate-change-related exposures, and trends in adaptive capacity. Box 8.5 describes trends in climate-change-related exposures of importance to human health. As highlighted in the following sections, particularly vulnerable populations and regions are more likely to suffer harm, have less ability to respond to stresses imposed by climate variability and change, and have exhibited limited progress in reducing current vulnerabilities. For example, all persons living in a flood plain are at risk during a flood, but those with lowered ability to escape floodwaters and their consequences (such as children and the infirm, or those living in sub-standard housing) are at higher risk.

8.4.2.1 Vulnerable urban populations

Urbanisation and climate change may work synergistically to increase disease burdens. Urban populations are growing faster in low-income than in high-income countries. The urban population increased from 220 million in 1900 to 732 million in 1950, and is estimated to have reached 3.2 billion in 2005 (UN, 2006b). In 2005, 74% of the population in more-developed regions was urban, compared with 43% in less-developed regions. Approximately 4.9 billion people are projected to be urban dwellers in 2030, about 60% of the global population, including 81% of the population in more-developed regions and 56% of the population in less-developed regions.

Urbanisation can positively influence population health; for example, by making it easier to provide safe water and improved sanitation. However, rapid and unplanned urbanisation is often

Box 8.5. Projected trends in climate-change-related exposures of importance to human health

Heatwaves, floods, droughts and other extreme events: IPCC (2007b) concludes, with high confidence, that heatwaves will increase, cold days will decrease over mid- to low-latitudes, and the proportion of heavy precipitation events will increase, with differences in the spatial distribution of the changes (although there will be a few areas with projected decreases in absolute numbers of heavy precipitation events) (Meehl et al., 2007). Water availability will be affected by changes in runoff due to alterations in the rainy and dry seasons.

Air quality: Climate change could affect tropospheric ozone by modifying precursor emissions, chemistry and transport; each could cause positive or negative feedbacks to climate change. Future climate change may cause either an increase or a decrease in background tropospheric ozone, due to the competing effects of higher water vapour and higher stratospheric input; increases in regional ozone pollution are expected, due to higher temperatures and weaker circulation. Future climate change may cause significant air-quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and aerosol generation, and the strength of emissions from the biosphere, fires and dust. The sign and magnitude of these effects are highly uncertain and will vary regionally (Denman et al., 2007).

Crop yields: Chapter 5 concluded that crop productivity is projected to increase slightly at mid- to high latitudes for local mean temperature increases of up to 1-3°C depending on the crop, and then decrease beyond that in some regions. At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C), which would increase the risk of hunger, with large negative effects on sub-Saharan Africa. Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk will suffer complex, localised impacts of climate change.

associated with adverse health outcomes. Urban slums and squatter settlements are often located in areas subject to landslides, floods and other natural hazards. Lack of water and sanitation in these settlements are not only problems in themselves, but also increase the difficulty of controlling disease reservoirs and vectors, facilitating the emergence and re-emergence of water-borne and other diseases (Obiri-Danso et al., 2001; Akhtar, 2002; Hay et al., 2005a). Combined with declining economies, unplanned urbanisation may affect the burden and control of malaria, with the disease burden increasing among urban dwellers (Keiser et al., 2004). Currently, approximately 200 million people in Africa (24.6% of the total population) live in urban settings where they are at risk of malaria. In India, unplanned urbanisation has contributed to the spread of *Plasmodium vivax* malaria (Akhtar et al., 2002) and dengue (Shah et al., 2004). In addition, noise, overcrowding and other possible features of unplanned urbanisation may increase the prevalence of mental disorders, such as depression, anxiety, chronic stress, schizophrenia and suicide (WHO, 2001). Problems associated with rapid and unplanned urbanisation are expected to increase over the next few decades, especially in low-income countries.

Populations in high-density urban areas with poor housing will be at increased risk with increases in the frequency and intensity of heatwaves, partly due to the interaction between increasing temperatures and urban heat-island effects (Wilby, 2003). Adaptation will require diverse strategies which could include physical modification to the built environment and improved housing and building standards (Koppe et al., 2004).

8.4.2.2 *Vulnerable rural populations*

Climate change could have a range of adverse effects on some rural populations and regions, including increased food insecurity due to geographical shifts in optimum crop-growing conditions and yield changes in crops, reduced water resources for agriculture and human consumption, flood and storm damage, loss of cropping land through floods, droughts, a rise in sea level, and increased rates of climate-sensitive health outcomes. Water scarcity itself is associated with multiple adverse health outcomes, including diseases associated with water contaminated with faecal and other hazardous substances (including parasites), vector-borne diseases associated with water-storage systems, and malnutrition (see Chapter 3). Water scarcity constitutes a serious constraint to sustainable development particularly in savanna regions: these regions cover approximately 40% of the world land area (Rockstrom, 2003).

8.4.2.3 *Food insecurity*

Although the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade projects that global cereal production could increase by 56% between 1997 and 2050, primarily in temperate regions, and livestock production by 90% (Rosegrant and Cline, 2003), expert assessments of future food security are generally pessimistic over the medium term. There are indications that it will take approximately 35 additional years to reach the World Food Summit 2002 target of reducing world hunger by half by 2015 (Rosegrant and Cline, 2003; UN Millennium Project, 2005). Child malnutrition is projected to persist in regions of low-income countries, although the total global burden is expected to decline without considering the impact of climate change.

Attribution of current and future climate-change-related malnutrition burdens is problematic because the determinants of malnutrition are complex. Due to the very large number of people that may be affected, malnutrition linked to extreme climatic events may be one of the most important consequences of climate change. For example, climate change is projected to increase the percentage of the Malian population at risk of hunger from 34% to between 64% and 72% by the 2050s, although this could be substantially reduced by the effective implementation of a range of adaptive strategies (Butt et al., 2005). Climate-change models project that those likely to be adversely affected are the regions already most vulnerable to food insecurity, notably Africa, which may lose substantial agricultural land. Overall, climate change is projected to increase the number of people at risk of hunger (FAO, 2005).

8.4.2.4 Populations in coastal and low-lying areas

One-quarter of the world's population resides within 100 km distance and 100 m elevation of the coastline, with increases likely over the coming decades (Small and Nicholls, 2003). Climate change could affect coastal areas through an accelerated rise in sea level; a further rise in sea-surface temperatures; an intensification of tropical cyclones; changes in wave and storm surge characteristics; altered precipitation/runoff; and ocean acidification (see Chapter 6). These changes could affect human health through coastal flooding and damaged coastal infrastructure; saltwater intrusion into coastal freshwater resources; damage to coastal ecosystems, coral reefs and coastal fisheries; population displacement; changes in the range and prevalence of climate-sensitive health outcomes; amongst others. Although some Small Island States and other low-lying areas are at particular risk, there are few projections of the health impact of climate variability and change. Climate-sensitive health outcomes of concern in Small Island States include malaria, dengue, diarrhoeal diseases, heat stress, skin diseases, acute respiratory infections and asthma (WHO, 2004a).

A model of a 4°C increase of the summer temperature maximum in the Netherlands in 2100, in combination with water column stratification, projected a doubling of the growth rates of selected species of potentially harmful phytoplankton in the North Sea, increasing the frequency and intensity of algal blooms that can negatively affect human health (Peperzak, 2005). Projections of impacts are complex because of substantial differences in the sensitivity to increasing ocean temperatures of phytoplankton harmful to human health.

The population at risk of flooding by storm surges throughout the 21st century has been projected based on a range of global mean sea-level rise and socio-economic scenarios (Nicholls, 2004). Under the baseline conditions, it was estimated that in 1990 about 200 million people lived beneath the 1-in-1,000-year storm surge height (e.g., people in the hazard zone), and about 10 million people/yr experienced flooding. Across all time slices, population growth increased the number of people living in a hazard zone under the four SRES scenarios (A1FI, A2, B1 and B2). Assuming that defences are upgraded against existing risks as countries become wealthier, but sea level rise is ignored, the number of people affected by flooding decreases by the 2080s under the A1FI, B1 and B2 scenarios. Under the A2 scenario, a two-to-three-fold increase is projected in the number of people flooded per year in the 2080s compared with 1990. Island regions are especially vulnerable, particularly in the A1FI world, especially in South-East Asia, South Asia, the Indian Ocean coast of Africa, the Atlantic coast of Africa and the southern Mediterranean (Nicholls, 2004).

Densely populated regions in low-lying areas are vulnerable to climate change. In Bangladesh, it is projected that 4.8% of people living in unprotected dryland areas could face inundation by a water depth of 30 to 90 cm based on assumptions of a 2°C temperature increase, a 30 cm increase in sea level, an 18% increase in monsoon precipitation, and a 5% increase in monsoon discharge into major rivers (BCAS/RA/Approtech, 1994). This could increase to 57% of people based on assumptions of a 4°C temperature increase, a 100 cm increase in sea level, a 33% increase in monsoon precipitation, and a 10% increase in monsoon discharge into major rivers. Some areas could face higher levels of inundation (90 to 180 cm).

Studies in industrialised countries indicate that densely populated urban areas are at risk from sea-level rise (see Chapter 6). As demonstrated by Hurricane Katrina, areas of New Orleans (USA) and its vicinity are 1.5 to 3 m below sea level (Burkett et al., 2003). Considering the rate of subsidence and using the TAR mid-range estimate of 480 mm sea-level rise by 2100, it is projected that this region could be 2.5 to 4.0 m or more below mean sea level by 2100, and that a storm surge from a Category 3 hurricane (estimated at 3 to 4 m without waves) could be 6 to 7 m above areas that were heavily populated in 2004 (Manuel, 2006).

8.4.2.5 Populations in mountain regions

Changes in climate are affecting many mountain glaciers, with rapid glacier retreat documented in the Himalayas, Greenland, the European Alps, the Andes Cordillera and East Africa (WWF, 2005). Changes in the depth of mountain snowpacks and glaciers, and changes in their seasonal melting, can have significant impacts on the communities from mountains to plains that rely on freshwater runoff. For example, in China, 23% of the population live in the western regions where glacial melt provides the principal dry season water source (Barnett et al., 2005). A long-term reduction in annual glacier snow melt could result in water insecurity in some regions.

Little published information is available on the possible health consequences of climate change in mountain regions. However, it is likely that vector-borne pathogens could take advantage of new habitats at altitudes that were formerly unsuitable, and that diarrhoeal diseases could become more prevalent with changes in freshwater quality and availability (WHO Regional Office for South-East Asia, 2006). More extreme rainfall events are likely to increase the number of floods and landslides. Glacier lake outburst floods are a risk unique to mountain regions; these are associated with high morbidity and mortality and are projected to increase as the rate of glacier melting increases.

8.4.2.6 Populations in polar regions

The approximately 10% of the circumpolar population that is indigenous is particularly vulnerable to climate change (ACIA, 2005). Factors contributing to their vulnerability include their close relationship with the land, location of communities in coastal regions, reliance on the local environment for aspects of their diet and economy, and socio-economic and other factors

(Berner and Furgal, 2005). The interactions of climate change with underlying social, cultural, economic and political trends are projected to have significant impacts on Arctic residents (Curtis et al., 2005).

Increasing winter temperatures in Arctic regions are projected to reduce excess winter mortality, primarily through a reduction in cardiovascular and respiratory deaths. A reduction in cold-related injuries is projected, assuming that cold protection, including human behavioural factors, does not change (Nayha, 2005). Observations in northern Canadian Aboriginal communities suggest that the number of land-based accidents and injuries associated with unpredictable environmental conditions such as thinning and earlier break-up of sea ice are likely to increase (e.g., Furgal et al., 2002a, b). Diseases transmitted by wildlife and insects are projected to have a longer season in some regions such as the north-western North American Arctic, resulting in increased burdens of disease in key animal species (e.g., marine mammals, birds, fish and shellfish) that can be transmitted to humans (Bradley et al., 2005; Parkinson and Butler, 2005). The traditional diet of circumpolar residents is likely to be negatively affected by changes in animal migrations and distribution, and human access to them, partly because of the impacts of increasing temperatures on snow and ice timing and distribution. Further, increasing temperatures may indirectly influence human exposure to environmental contaminants in some foods (e.g., marine mammal fats). Temperature increases in the North Atlantic are projected to increase rates of mercury methylation in fish and marine mammals, thus increasing human exposure via consumption (Booth and Zeller, 2005).

8.5 Costs

Studies focusing on the welfare costs (and benefits) of climate-change impacts aggregate the 'damage' costs of climate change (Tol, 1995, 1996, 2002a, b; Fankhauser and Tol, 1997; Fankhauser et al., 1997) or estimate the costs and benefits of measures to reduce climate change (Nordhaus, 1991; Cline, 1992, 2004; Nordhaus and Boyer, 2000). The global economic value of loss of life due to climate change ranges between around US$6 billion and US$88 billion, in 1990 dollar prices (Tol, 1995, 1996, 2002a, b; Fankhauser and Tol, 1997; Fankhauser et al., 1997). The economic methods for estimating welfare costs (and benefits) have several shortcomings; the studies include only a limited number of health outcomes, generally heat- and cold-related mortality and malaria. Some assessments of the direct costs of health impacts at the national level have been undertaken, but the evidence base for estimating the health effects is relatively weak (IGCI, 2000; Turpie et al., 2002; Woodruff et al., 2005). Where they have been estimated, the welfare costs of health impacts contribute substantially to the total costs of climate change (Cline, 1992; Tol, 2002a). Given the importance of these types of assessments, further research is needed.

Mortality attributable to climate change is projected to be greatest in low-income countries, where economists traditionally assign a lower value to life (van der Pligt et al., 1998; Hammitt and Graham, 1999; Viscusi and Aldy, 2003). Some estimates suggest that replacing national values with a 'global average value' would increase the mortality costs by as much as five times (Fankhauser et al., 1997). Climate change is also likely to have important direct effects on productivity via exposure of workers to heat stress (see Section 8.2.9). Estimates of economic impacts via changes in productivity ignore important health impacts in children and the elderly. Further research is needed to estimate productivity costs.

8.6 Adaptation: practices, options and constraints

Adaptation is needed now in order to reduce current vulnerability to the climate change that has already occurred and additional adaptation is needed in order to address the health risks projected to occur over the coming decades. Current levels of vulnerability are partly a function of the programmes and measures in place to reduce burdens of climate-sensitive health determinants and outcomes, and partly a result of the success of traditional public-health activities, including providing access to safe water and improved sanitation to reduce diarrhoeal diseases, and implementing surveillance programmes to identify and respond to outbreaks of malaria and other infectious diseases. Weak public-health systems and limited access to primary health care contribute to high levels of vulnerability and low adaptive capacity for hundreds of millions of people.

Current national and international programmes and measures that aim to reduce the burdens of climate-sensitive health determinants and outcomes may need to be revised, reoriented and, in some regions, expanded to address the additional pressures of climate change. The degree to which programmes will need to be augmented will depend on factors such as the current burden of climate-sensitive health outcomes, the effectiveness of current interventions, projections of where, when and how the burden could change with changes in climate and climate variability, access to the human and financial resources needed to implement activities, stressors that could increase or decrease resilience to impacts, and the social, economic and political context within which interventions are implemented (Yohe and Ebi, 2005; Ebi et al., 2006a). Some recent programmes and measures implemented to address climate variability and change are highlighted in the examples that follow.

The planning horizon of public-health decision-makers is short relative to the projected impacts of climate change, which will require modification of current risk-management approaches that focus only on short-term risks (Ebi et al., 2006b). A two-tiered approach may be needed, with modifications to incorporate current climate change concerns into ongoing programmes and measures, along with regular evaluations to determine a programme's likely effectiveness to cope with projected climate risks. For example, epidemic malaria is a public-health problem in most areas in Africa, with programmes in place to reduce the morbidity and mortality associated with these epidemics. Some projections suggest that climate change may facilitate the spread of malaria further up some highland areas (see Section 8.4.1.2). Therefore, programmes should not only continue their current focus, but should also consider where and when to implement additional surveillance to identify and prevent epidemics if the *Anopheles* vector changes its range.

How public health and other infrastructure will develop is a key uncertainty (see Section 8.3) that is not determined by GDP per capita alone. Public awareness, effective use of local resources, appropriate governance arrangements and community participation are necessary to mobilise and prepare for climate change (McMichael, 2004). These present particular challenges in low-income countries. Furthermore, the status of and trends in other sectors affect public health, particularly water quantity, quality and sanitation (see Chapter 3), food quality and quantity (see Chapter 5), the urban environment (see Chapter 7), and ecosystems (see Chapter 4). These sectors will also be affected by climate change, creating feedback loops that can increase or decrease population vulnerability, particularly in low-income countries (Figure 8.1).

8.6.1 Approaches at different scales

Pro-active adaptation strategies, policies and measures need to be implemented by regional and national governments, including Ministries of Health, by international organisations such as the World Health Organization, and by individuals. Because the range of possible health impacts of climate change is broad and the local situations diverse, the examples that follow are illustrative and not comprehensive.

8.6.1.1 National- and regional-level responses

Climate-based early warning systems for heatwaves and malaria outbreaks have been implemented at national and local levels to alert the population and relevant authorities that a disease outbreak can be expected based on climatic and environmental forecasts (Abeku et al., 2004; Teklehaimanot et al., 2004; Thomson et al., 2005; Kovats and Ebi, 2006). To be effective in reducing health impacts, such systems must be coupled with a specific intervention plan and have an ongoing evaluation of the system and its components (Woodruff et al., 2005; Kovats and Ebi, 2006).

Seasonal forecasts can be used to increase resilience to climate variability, including to weather disasters. For example, the Pacific ENSO Application Center (PEAC) alerted governments, when a strong El Niño was developing in 1997/1998, that severe droughts could occur, and that some islands were at unusually high risk of tropical cyclones (Hamnett, 1998). The interventions launched, such as public education and awareness campaigns, were effective in reducing the risk of diarrhoeal and vector-borne diseases. For example, despite the water shortage in Pohnpei, fewer children were admitted to hospital with severe diarrhoeal disease than normal because of frequent public-health messages about water safety. However, the interventions did not eliminate all negative health impacts, such as micronutrient deficiencies in pregnant women in Fiji.

Participatory approaches that include governments, researchers and community residents are increasingly being used to build awareness of climate-related health impacts and adaptation options, and to take advantage of local knowledge and perspectives (see Box 8.6).

8.6.1.2 Responses by international organisations and agencies

Improvements in international surveillance systems facilitate national and regional preparedness and reduce future vulnerability to epidemic-prone diseases. At present, surveillance systems in many parts of the world are incomplete and slow to respond to disease outbreaks. It is expected that this will improve through the implementation of the International Health Regulations. Improvements in the responsiveness and accuracy of current surveillance programmes, including addressing spatial and temporal limitations, are needed to account for and anticipate the increased pressures on disease-control programmes that are projected to result from climate change. Earth observations, monitoring and surveillance, such as remote sensing and biosensors, may increase the accuracy and precision of some of these activities (Maynard, 2006).

Donors, international and national aid agencies, emergency relief agencies, and a range of non-governmental organisations play key roles through direct aid, support of research and development, and other approaches developed in conjunction with national Ministries of Health to improve current public-health responses and to more effectively incorporate climate-change-related risks into the design, implementation and evaluation of disease-control policies and measures.

Box 8.6. Cross-cutting case study: indigenous populations and adaptation

A series of workshops organised by the national Inuit organisation in Canada, Inuit Tapiriit Kantami, documented climate-related changes and impacts, and identified and developed potential adaptation measures for local response (Furgal et al., 2002a, b; Nickels et al., 2003). The strong engagement of Inuit community residents will facilitate the successful adoption of the adaptation measures identified, such as using netting and screens on windows and house entrances to prevent bites from mosquitoes and other insects that have become more prevalent.

Another example is a study of the links between malaria and agriculture that included participation and input from a farming community in Mwea division, Kenya (Mutero et al., 2004). The approach facilitated identification of opportunities for long-term malaria control in irrigated rice-growing areas through the integration of agro-ecosystem practices aimed at sustaining livestock systems within a broader strategy for rural development.

Two or more countries can develop international responses jointly when adverse health outcomes and their drivers cross borders. For example, flood prevention guidelines were developed through the United Nations Economic Commission for Europe for countries along the Elbe, Danube, Rhine and other transboundary rivers where floods have intensified due to human alteration of the environment (UN, 2000). The guidelines recognise that co-operation is needed both within and between riparian countries in order to reduce current impacts and increase future resilience.

8.6.1.3 Individual-level responses

The effectiveness of warning systems for extreme events depends on individuals taking appropriate actions, such as responding to heat alerts and flood warnings. Individuals can reduce their personal exposure by adjusting clothing and activity levels in response to high ambient temperatures and by modifying built environments, such as by the use of fans, to reduce the heat load (Davis et al., 2004; Kovats and Koppe, 2005). Weather can partially determine cultural practices that may affect exposure.

8.6.1.4 Adaptation in health systems

Health systems need to plan for and respond to climate change (Menne and Bertollini, 2005). There are effective interventions for many of the most common causes of ill-health, but frequently these interventions do not reach those who could benefit most. One way of promoting adaptation and reducing vulnerability to climate change is to promote the uptake of effective clinical and public-health interventions in high-need cities and regions of the world. For example, health in Africa must be treated as a high priority investment in the international development portfolio (Sachs, 2001). Funding health programmes is a necessary step towards reducing vulnerability but will not be enough on its own (Brewer and Heymann, 2004; Regidor, 2004a, b; de Vogli et al., 2005; Macintyre et al., 2005). Progress depends also on strengthening public institutions; building health systems that work well, treating people fairly and providing universal primary health care; providing adequate education, generating demand for better and more accessible services; and ensuring that there are enough staff to do the required work (Haines and Cassels, 2004). Health-service infrastructure needs to be resilient to extreme events (EEA, 2005). Efforts are needed to train health professionals to understand the threats posed by climate change.

8.6.2 Integration of responses across scales

Adaptation responses to specific health risks will often cut across scales. For example, an integrated response to heatwaves could include, in addition to measures already discussed, consideration of climate change projections in the design and construction of new buildings and in the planning of new urban areas (Kovats and Koppe, 2005). In addition, national energy efficiency programmes and transport policies could include approaches for reducing both urban heat islands and emissions of ozone and other air pollutants.

Interventions designed to increase the adaptive capacity of a community or region could also facilitate the achievement of greenhouse gas mitigation targets. For example, measures to reduce the urban heat-island effect, such as planting trees, roof gardens, growth planned to reduce urban heat islands, and other measures, increase the resilience of communities to heatwaves while reducing energy requirements. Increasing the proportion of energy derived from solar, wind and other renewable resources would reduce emissions of greenhouse gases and other air pollutants from the burning of fossil fuels.

8.6.3 Limits to adaptation

Constraints to adaptation arise when one or more of the prerequisites for public-health prevention have not been met: an awareness that a problem exists; a sense that the problem matters; an understanding of what causes the problem; the capability to influence; and the political will to influence the problem (Last, 1998). Decision-makers will choose which adaptations to implement where, when and how, based on assessments of the balance between competing priorities (Scheraga et al., 2003). For example, different regions may make different assessments of the public-health and environmental-welfare implications of the ecological consequences of draining wetlands to reduce vector-breeding sites. Local laws and social customs may constrain adaptation options. For example, although the application of pesticides for vector control may be an effective adaptation measure, residents may object to spraying, even in communities with regulations to assure appropriate use. Increasing awareness of climate-change-related health impacts and knowledge diffusion of adaptation options are of fundamental importance to better decision-making.

Although specific limits will vary by health outcome and region, fundamental constraints exist in low-income countries where adaptation will partially depend on development pathways in the public-health, water, agriculture, transport, energy and housing sectors. Poverty is the most serious obstacle to effective adaptation. Despite economic growth, low-income countries are likely to remain poor and vulnerable over the medium term, with fewer options than high-income countries for adapting to climate change. Therefore, adaptation strategies should be designed in the context of development, environment, and health policies. Many of the options that can be used to reduce future vulnerability are of value in adapting to current climate and can be used to achieve other environmental and social objectives. However, because resources used for adaptation will be shared across other problems of concern to society, there is the potential for conflicts among stakeholders with differing priorities. Questions also will arise about equity (i.e., a decision that leads to differential health impacts among different demographic groups), efficiency (i.e., targeting those programmes that will yield the greatest improvements in public health), and political feasibility (McMichael et al., 2003a).

8.6.4 Health implications of adaptation strategies, policies and measures

Because adaptation strategies, policies and measures can have inadvertent short- and long-term negative health consequences, potential risks should be evaluated before implementation. For example, a microdam and irrigation programme in Ethiopia developed to increase resilience to famine increased local malaria mortality by 7.3-fold (Ghebreyesus et al., 1999). Increased ambient temperatures due to climate change could further exacerbate the problem. In another example, air-conditioning of private and public spaces is a primary measure used in the USA to reduce heat-related morbidity and mortality (Davis et al., 2003); however, depending on the energy source used to generate electricity, an increased use of air conditioning can increase greenhouse gas emissions, air pollution and the urban heat island.

Measures to combat water scarcity, such as the re-use of wastewater for irrigation, have implications for human health (see Chapter 3). Irrigation is currently an important determinant of the spread of infectious diseases such as malaria and schistosomiasis (Sutherst, 2004). Strict water-quality guidelines for wastewater irrigation are designed to prevent health risks from pathogenic organisms and to guarantee crop quality (Steenvoorden and Endreny, 2004). However, in rural and peri-urban areas of most low-income countries, the use of sewage and wastewater for irrigation, a common practice, is a source of faecal–oral disease transmission. The use of wastewater for irrigation is likely to increase with climate change, and the treatment of wastewater remains unaffordable for low-income populations (Buechler and Scott, 2000)

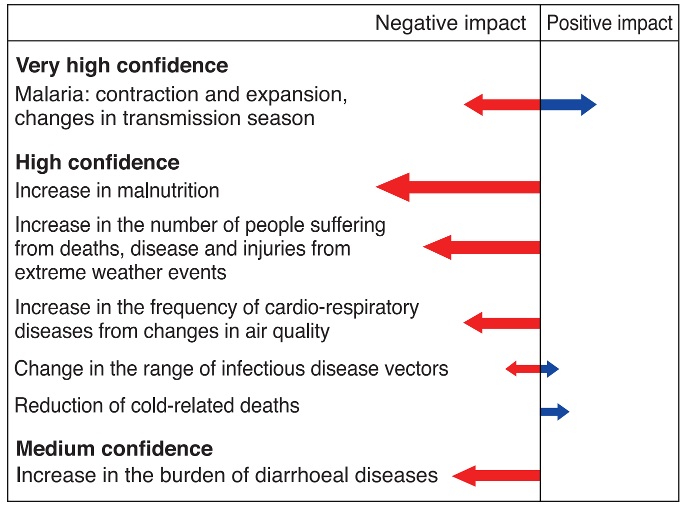

Figure 8.3. *Direction and magnitude of change of selected health impacts of climate change (confidence levels are assigned based on the IPCC guidelines on uncertainty, see http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf).*

8.7 Conclusions: implications for sustainable development

Evidence has grown that climate change already contributes to the global burden of disease and premature deaths. Climate change plays an important role in the spatial and temporal distribution of malaria, dengue, tick-borne diseases, cholera and other diarrhoeal diseases; is affecting the seasonal distribution and concentrations of some allergenic pollen species; and has increased heat-related mortality. The effects are unequally distributed, and are particularly severe in countries with already high disease burdens, such as sub-Saharan Africa and Asia.

The projected health impacts of climate change are predominately negative, with the most severe impacts being seen in low-income countries, where the capacity to adapt is weakest. Vulnerable groups in developed countries will also be affected (Haines et al., 2006). Projected increases in temperature and changes in rainfall patterns can increase malnutrition; disease and injury due to heatwaves, floods, storms, fires and droughts; diarrhoeal illness; and the frequency of cardio-respiratory diseases due to higher concentrations of ground-level ozone. There are expected to be some benefits to health, including fewer deaths due to exposure to the cold and reductions in climate suitability for vector-borne diseases in some regions. Figure 8.3 summarises the relative direction and magnitude of projected health impacts, taking into account the likely numbers of people at risk and potential adaptive capacity.

Health is central to the achievement of the Millennium Development Goals and to sustainable development, both directly (in the case of child mortality, maternal health, HIV/AIDS, malaria and other diseases) and indirectly (ill-health contributes to extreme poverty, hunger and lower educational achievements) (Haines and Cassels, 2004). Rapid and intense climate change is likely to delay progress towards achieving development targets in some regions. Recent events demonstrate that populations and health systems may be unable to cope with increases in the frequency and intensity of extreme events. These events can reduce the resilience of communities, affect vulnerable regions and localities, and overwhelm the coping capacities of most societies.

There is a need to develop and implement adaptation strategies, policies and measures at different levels and scales. Current national and international programmes and measures that aim to reduce the burdens of climate-sensitive health determinants and outcomes may need to be revised, reoriented and, in some regions, expanded to address the additional pressures of climate change. This includes the consideration of climate-change-related risks in disease monitoring and surveillance systems, health system planning, and preparedness. Many of the health outcomes are mediated through changes in the environment. Measures implemented in the water, agriculture, food, and construction sectors should be designed to benefit human health. However, adaptation is not enough.

8.7.1 Health and climate protection: clean energy

There is general agreement that health co-benefits from reduced air pollution as a result of actions to reduce GHG emissions can be substantial and may offset a substantial fraction of mitigation costs (Barker et al., 2001, 2007; Cifuentes et al., 2001; West et al., 2004). In addition, actions to reduce methane emissions will decrease global concentrations of surface ozone. A portfolio of actions, including energy efficiency, renewable energy, and transport measures, is needed in order to achieve these reductions (see IPCC, 2007c).

In many low-income countries, access to electricity is limited. Over half of the world's population still relies on biomass fuels and coal to meet their energy needs (WHO, 2006). These biomass fuels have low combustion efficiency and a significant, but unknown, portion is harvested non-renewably, thus contributing to net carbon emissions. The products of incomplete combustion from small-scale biomass combustion contain a number of health-damaging pollutants, including small particles, carbon monoxide, polyaromatic hydrocarbons and a range of toxic volatile organic compounds (Bruce et al., 2000). Human exposures to these pollutants within homes are large in comparison with outdoor air pollution exposures. Current best estimates, based on published epidemiological studies, are that biomass fuels in households are responsible annually for approximately 0.7 to 2.1 million premature deaths in low-income countries (from a combination of lower-respiratory infections, chronic obstructive pulmonary disease and lung cancer). About two-thirds occur in children under the age of five and most of the rest occur in women (Smith et al., 2004).

Clean development and other mechanisms could require calculation of the co-benefits for health when taking decisions about energy projects, including the development of alternative fuel sources (Smith et al., 2000, 2005). Projects promoting co-benefits in low-income populations show promise to help achieve cost-effective, long-term protection from climate impacts as well as promoting immediate sustainable development goals (Smith et al., 2000).

8.8 Key uncertainties and research priorities

More empirical epidemiological research on the observed health effects of climate change have been published since the TAR, and the few national health impact assessments that have been conducted have provided valuable information on population vulnerability. However, the lack of appropriate longitudinal health data makes attribution of adverse health outcomes to observed climate trends difficult. Further, most studies have focused on middle- and high-income countries. Gaps in information persist on trends in climate, health and environment in low-income countries, where data are limited and other health priorities take precedence for research and policy development. Climate-change-related health impact assessments in low- and middle-income countries will be instrumental in guiding adaptation projects and investments.

Advances have been made in the development of climate–health impact models that project the health effects of climate change under a range of climate and socio-economic scenarios. The models are still limited to a few infectious diseases, thermal extremes and air pollution. Considerable uncertainties surround the projections, including uncertainty about how population health is likely to evolve based on changes in the level of commitment to preventing avoidable ill-health, technological developments, economic growth and other factors; the rate and intensity of future climate change; uncertainty about how the climate–health relationship might change over time; and uncertainty about the extent, rate, limiting forces and major drivers of adaptation (McMichael et al., 2004). Uncertainties include not just whether the key health outcomes described in this chapter will improve, but how fast, where, when, at what cost, and whether all population groups will be able to share in these developments. Significant advances will occur by improving social and economic development, governance and resources. It is apparent that these problems will only be solved over time-frames longer than decades.

Considerable uncertainty will remain about projected climate change at geographical and temporal scales of relevance to decision-makers, increasing the importance of risk management approaches to climate risks. However, no matter what the degree of preparedness is, projections suggest that some future extreme events will be catastrophic because of the unexpected intensity of the event and the underlying vulnerability of the affected population. The European heatwave in 2003 and Hurricane Katrina are examples. The consequences of particularly severe extreme events will be greater in low-income countries. A better understanding is needed of the factors that convey vulnerability and, more importantly, the changes that need to be made in health care, emergency services, land use, urban design and settlement patterns to protect populations against heatwaves, floods, and storms.

Key research priorities include addressing the major challenges for research on climate change and health in the following ways.

- Development of methods to quantify the current impacts of climate and weather on a range of health outcomes, particularly in low- and middle-income countries.
- Development of health-impacts models for projecting climate-change-related impacts under different climate and socio-economic scenarios.
- Investigations on the costs of the projected health impacts of climate change; effectiveness of adaptation; and the limiting forces, major drivers and costs of adaptation.

Low-income countries face additional challenges, including limited capacity to identify key issues, collect and analyse data, and design, implement and monitor adaptation options. There is a need to strengthen institutions and mechanisms that can more systematically promote interactions among researchers, policy-makers and other stakeholders to facilitate the appropriate incorporation of research findings into policy decisions in order to protect population health no matter what the climate brings (Haines et al., 2004).

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