Chapter 11. Human Health: Impacts, Adaptation, and Co-Benefits

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Executive Summary

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and occurrence of heat waves, floods, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. [11.4] Biological and social adaptation is more difficult in a highly variable climate than one that is more stable. [11.7]

Until mid-century climate change will act mainly by exacerbating health problems that already exist *[very high confidence]*. New conditions may emerge under climate change *[low confidence]*, and existing diseases (e.g. food-borne infections) may extend their range into areas that are presently unaffected *[high confidence]*. But the largest risks will apply in populations that are currently most affected by climate-related diseases. Thus, for example, it is expected that health losses due to climate change-induced under-nutrition will occur mainly in areas that are already food-insecure. [11.3]

In recent decades, climate change has contributed to levels of ill-health (*likely*) though the present world-wide burden of ill-health from climate change is relatively small compared with other stressors on health and is not well quantified. Rising temperatures have increased the risk of heat-related death and illness *(likely)*. [11.4] Local changes in temperature and rainfall have altered distribution of some water-borne illnesses and disease vectors, and reduced food production for some vulnerable populations *[medium confidence]*. [11.5, 11.6]

If climate change continues as projected across the RCP scenarios until mid-century, the major increases of ill-health compared to no climate change will occur through:

- Greater risk of injury, disease, and death due to more intense heat waves and fires *[very high confidence]* [11.4]
- Increased risk of under-nutrition resulting from diminished food production in poor regions *[high confidence]* [11.6]
- Consequences for health of lost work capacity and reduced labor productivity in vulnerable populations *[high confidence]* [11.6]
- Increased risks of food- and water-borne diseases *[very high confidence]* and vector-borne diseases *[medium confidence]* [11.5]
- Modest improvements in cold-related mortality and morbidity in some areas due to fewer cold extremes *[low confidence]*, geographical shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds *[medium confidence]*. These positive effects will be out-weighed, world-wide, by the magnitude and severity of the negative effects of climate change *[high confidence]*. [11.4, 11.5, 11.6]

Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development *[high confidence]*, particularly among the poorest and least healthy groups *[very high confidence]*.

[11.4, 11.6, 11.7] Climate change is an impediment to continued health improvements in many parts of the world. If economic growth does not benefit the poor, the health effects of climate change will be exacerbated.

In addition to their implications for climate change, essentially all the important Climate Altering Pollutants (CAPs) other than CO_2 have near-term health implications *[very high confidence*]. In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants [*high confidence*]. [Box 11-4]

Some parts of the world already exceed the international standard for safe work activity during the hottest months of the year. The capacity of the human body to thermoregulate may be exceeded on a regular basis, particularly during manual labour, in parts of the world during this century. In the highest Representative Concentration Pathway, RCP8.5, by 2100 some of the world's land area will be experiencing 4-7 degree higher temperatures due to anthropogenic climate change [WG1, Figure SPM.7]. If this occurs, the combination of high temperatures and high humidity will compromise normal human activities, including growing food or working outdoors, raising doubt about the habitability of some areas, for parts of the year *[high confidence]*. [11.8]

The most effective adaptation measures for health in the near-term are programs that implement basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty *[very high confidence*]. [11.7] In addition, there has been progress since AR4 in targeted and climate-specific measures to protect health, including enhanced surveillance and early warning systems. [11.7]

There are opportunities to achieve co-benefits from actions that reduce emissions of CAPs and at the same time improve health. Among others, these include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy systems, through improved energy efficiency, and a shift to cleaner energy sources *[very high confidence]* [11.9]
- Providing access to reproductive health services (including modern family planning) to improve child and maternal health through birth spacing and reduce population growth, energy use, and consequent CAP emissions over time *[medium confidence]* [11.9]
- Shifting consumption away from animal products, especially from ruminant sources, in high-meat-consumption societies toward less CAP-intensive healthy diets *[medium confidence]* [11.9]
- Designing transport systems that promote active transport and reduce use of motorized vehicles, leading to lower emissions of CAPs and better health through improved air quality and greater physical activity *[high confidence]* [11.9].

There are important research gaps regarding the health consequences of climate change and co-benefits actions, particularly in low-income countries. There are now opportunities to use existing longitudinal data on population health to investigate how climate change affects the most vulnerable populations. Another gap concerns the scientific evaluation of the health implications of adaptation measures at community and national levels. A further challenge is to improve understanding of the extent to which taking health co-benefits into account can offset the costs of GHG mitigation strategies.

11.1. Introduction

This chapter examines what is known about the effects of climate change on human health and, briefly, the more direct impacts of Climate-Altering Pollutants (CAPs, see glossary) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that influence the susceptibility of populations and individuals to ill-health due to variations in weather and climate, and describe steps that may be taken to reduce the impacts of climate change on human health. The chapter also includes a section on health "co-benefits." Co-benefits are positive effects on human health that arise from interventions to reduce emissions of CAPs or vice versa.

This is a scientific assessment based on best available evidence according to the judgment of the authors. We searched the English-language literature up to August 2013, focusing primarily on publications since 2007. We drew primarily (but not exclusively) on peer-reviewed journals. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field. We examined recent substantial reviews (for instance (Bassil and Cole, 2010; Gosling *et al.*, 2009; Hajat *et al.*, 2010; Huang *et al.*, 2011; McMichael, 2013b; Stanke *et al.*, 2013)), to check for any omissions of important work. In selecting citations for the chapter, we gave priority to publications that were recent (since AR4), comprehensive, added significant new findings to the literature, included areas or population groups that have not previously been well-described or were judged to be particularly policy-relevant in other respects.

We begin with an outline of measures of human health, the major driving forces that act on health world-wide, recent trends in health status, and health projections for the remainder of this century.

11.1.1. Present State of Global Health

The Fourth Assessment Report pointed to dramatic improvement in life expectancy in most parts of the world in the 20th Century, and this trend has continued through the first decade of the 21st century (Wang, 2012). Rapid progress in a few countries (especially China) has dominated global averages, but most countries have benefited from substantial reductions in mortality. There remain sizable and avoidable inequalities in life expectancy within- and between-nations in terms of education, income and ethnicity (Beaglehole and Bonita, 2008) and in some countries, official statistics are so patchy in quality and coverage that it is difficult to draw firm conclusions about health trends (Byass, 2010). Years lived with disability have tended to increase in most countries (Salomon *et al.*, 2012).

If economic development continues as forecast, it is expected that mortality rates will continue to fall in most countries; WHO estimates the global burden of disease (measured in Disability Adjusted Life Years per capita) will decrease by 30% by 2030, compared with 2004 (World Health Organization, 2008a; World Health Organization, 2008b). The underlying causes of global poor health are expected to change substantially, with much greater prominence of chronic diseases and injury, nevertheless the major infectious diseases of adults and children will remain important in some regions, particularly Sub-Saharan Africa and South Asia (Hughes *et al.*, 2011).

11.1.2. Developments since AR4

The relevant literature has grown considerably since publication of AR4. For instance, the annual number of MEDLINE citations on climate change and health doubled between 2007 and 2009 (Hosking and Campbell-Lendrum, 2012). In addition, there have been many reviews, reports and international assessments that do not appear in listings such as MEDLINE but include important information nevertheless, for instance, the World Development Report 2010 (World Bank, 2010) and the 2011 UN Habitat report on cities and climate change (United Nations Human Settlements Programme, 2011). Since AR4, there have been improvements in the methods applied to investigate climate change and health. These include more sophisticated modeling of possible future impacts (for example, work linking climate change, food security, and health outcomes) (Nelson *et al.*, 2010) and new methods to model the effects of heat on work capacity and labor productivity (Kjellstrom *et al.*, 2009b). Other developments include coupling of high-quality, longitudinal mortality data sets with down-scaled meteorological data, in low-income settings (for instance, through the INDEPTH Network) (see Box 11-1).

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Box 11-1. Weather, Climate, and Health –
a Long-Term Observational Study in African and Asian Populations

Given the dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries, we report on a project that spans sub-Saharan Africa and Asia. The INDEPTH Network currently includes 43 surveillance sites in 20 countries. Using standardized health and demographic surveillance systems, member sites have collected up to 45 years information on births, migration and deaths. Currently, there are about 3.2 million people under surveillance (Sankoh and Byass, 2012).

To study relationships between weather and health, the authors obtained daily meteorological data for 12 INDEPTH populations between 2000 and 2009, and projected future climate changes to 2100 under the A1B, A3, and B1 scenarios (Hondula *et al.*, 2012). The authors concluded the health of all the populations would be challenged by the new climatic conditions, especially later in the century. In another study from the Network, Diboulo *et al.* (2012) examined the relation between weather and all-cause mortality data in Burkina Faso. Relations between daily temperature and mortality were similar to those reported in many high-income settings, and susceptibility to heat varied by age and gender.

_____ END BOX 11-1 HERE _____

Since AR4, studies of the ways in which policies to reduce GHG emissions may affect health, or vice versa, leading to so-called “co-benefits” in the case of positive outcomes for either climate or health, have multiplied (Haines *et al.*, 2009).

Much has been written on links between climate, socioeconomic conditions and health, for example related to occupational heat exposure (Kjellstrom *et al.*, 2009b) and malaria (e.g., Béguin *et al.*, 2011; Gething *et al.*, 2010) There is also growing appreciation of the social upheaval and damage to population health that may arise from the interaction of large-scale food insecurity, population dislocation, and conflict (see Chapter 12).

11.1.3. Non-Climate Health Effects of Climate-Altering Pollutants (CAPs)

CAPs affect health in other ways than through climate change, just as CO_2 creates non-climate effects such as ocean acidification. The effects of rising CO_2 levels on calcifying marine species are well documented and the risks for coral reefs are now more closely defined than they were at the time of the AR4 (see Chapter 30). There are potential implications for human health, such as under-nutrition in coastal populations that depend on local fish stocks, but, so far, links between health and ocean acidification have not been closely studied (Kite-Powell *et al.*, 2008). CAPs such as black carbon and tropospheric ozone have substantial, direct, negative effects on human health (Wang *et al.*, 2013). (See 11.5.3 and Box 11-3.) Although CO_2 is not considered a health-damaging air pollutant at levels experienced outside particular occupational and health-care settings, one study has reported a reduction in mental performance at 1000 ppm and above, within the range that all of humanity would experience in some extreme climate scenarios by 2100 (Satish *et al.*, 2012).

11.2. How Climate Change Affects Health

There are three basic pathways by which climate change affects health (Figure 11-1), and these provide the organization for the chapter:

- Direct impacts, which relate primarily to changes in the frequency of extreme weather including heat, drought, and heavy rain [11.4]
- Effects mediated through natural systems, for example, disease vectors, water-borne diseases, and air pollution [11.5]
- Effects heavily mediated by human systems, for example, occupational impacts, undernutrition, and mental stress [11.6].

[INSERT FIGURE 11-1 HERE
Figure 11-1: Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The yellow box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The orange box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback

mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health. Credit: E. Garcia, UC Berkeley.]

The negative effects of climate change on health may be reduced by improved health services, better disaster management, and poverty alleviation, although the cost and effort may be considerable [11.7]. The consequences of large magnitude climate change beyond 2050, however, would be much more difficult to deal with [11.8]. Although there are exceptions, to a first approximation climate change acts to exacerbate existing patterns of ill-health, by acting on the underlying vulnerabilities that lead to ill-health even without climate change. Thus, before pursuing the three pathways in Figure 11-1, we summarize what is known about vulnerability to climate-induced illness and injury.

11.3. Vulnerability to Disease and Injury due to Climate Variability and Climate Change

In the IPCC assessments, vulnerability is defined as the propensity or predisposition to be adversely affected (see Chapter 19 and Glossary). In this section, we consider causes of vulnerability to ill-health associated with climate change and climate variability, including individual and population characteristics and factors in the physical environment.

We have outlined the causes of vulnerability separately, but in practice causes combine, often in a complex and place-specific manner. There are some factors (such as education, income, health status and responsiveness of government) that act as generic causes of vulnerability. For example, the quality of governance – how decisions are made and put into practice – affects a community's response to threats of all kinds (Bowen *et al.*, 2012). (See Chapter 12.) The background climate-related disease rate of a population is often the best single indicator of vulnerability to climate change - doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high. (Note that here, and elsewhere in the chapter, we treat "risk" in the epidemiological sense: the probability that an event will occur.) But the precise causes of vulnerability, and therefore the most relevant adaptation capacities, vary greatly from one setting to another. For example, severe drought in Australia has been linked to psychological distress – but only for those residing in rural and remote areas (Berry *et al.*, 2010). The link between high ambient temperatures and increased incidence of salmonella food poisoning has been demonstrated in many places (e.g. (Zhang *et al.*, 2010)), but the lag varies from one country to another, suggesting that the mechanisms differ. Deficiencies in food storage may be the critical link in some places, food handling problems may be most important elsewhere (Kovats *et al.*, 2004).

The 2010 World Development Report concluded that all developing regions are vulnerable to economic and social damage resulting from climate change – but for different reasons (World Bank, 2010). The critical factors for Sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that may be amplified in parts of the region under climate change, sparse infrastructure and high dependence on natural resources (see Chapter 22). Asia and the Pacific, on the other hand, are distinguished by the very large number of people living in low-lying areas prone to flooding (see Chapters 24 and 29).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for health losses caused by climate change (Samson *et al.*, 2011). Those working outdoors in countries where temperatures in the hottest time of the year are already at the limits of thermal tolerance for part of the year will be more severely affected by further warming than workers in cooler countries (Kjellstrom *et al.*, 2013). The inhabitants of low-lying coral atolls are very sensitive to flooding, contamination of fresh water reservoirs due to sea level rise, and salination of soil, all of which may have important effects on health (Nunn, 2009). Rural populations that rely on subsistence farming in low rainfall areas are at high risk of under-nutrition and water-related diseases if drought occurs, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik *et al.*, 2008). Living in rural and remote areas may confer increased risk of ill-health because of limited access to services and generally higher levels of social and economic disadvantage (Smith, 2008). Populations that are close to the present limits of transmission of vector-borne diseases are most vulnerable to changes in the range of transmission due to rising temperatures and altered patterns of rainfall, especially when disease control systems are weak (Lozano-Fuentes *et al.*, 2012; Zhou *et al.*, 2008). In cities, those who live on urban heat islands are at greater risk of ill-health due to extreme heat events (Stone *et al.*, 2010; Uejio *et al.*, 2011).

11.3.2. Current Health Status

Climate extremes may promote the transmission of certain infectious diseases and the vulnerability of populations to these diseases will depend on the baseline levels of pathogens and their vectors. In the United States, as one example, arboviral diseases such as dengue are rarely seen after flooding, compared with the experience in other parts of the Americas. The explanation lies in the scarcity of dengue (and other pathogenic viruses) circulating in the population, before the flooding (Keim, 2008). On the other hand, the high prevalence of HIV infection in many populations in Sub-Saharan Africa will tend to multiply the health risks of climate change, due to the interactions between chronic ill-health, poverty, extreme weather events and undernutrition (Ramin and McMichael, 2009). Chronic diseases such as diabetes and ischemic heart disease magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki *et al.*, 2009).

11.3.3. Age and Gender

Children, young people, and the elderly are at increased risk of climate-related injury and illness (Perera, 2008). For example, adverse effects of malaria, diarrhea, and undernutrition are presently concentrated amongst children, for reasons of physiological susceptibility (Michon *et al.*, 2007). In principle, children are thought to be more vulnerable to heat-related illnesses, due to their small body mass to surface area ratio, but evidence of excess heat-related mortality in this age group is mixed (Basu and Ostro, 2008; Kovats and Hajat, 2008). Maternal antibodies acquired *in utero* provide some protection against dengue fever in the first year of life, but if infection does occur in infants it is more likely to provoke the severe hemorrhagic form of illness (Ranjit and Kissoon, 2011). Children are generally at greater risk when food supplies are restricted: households with children tend to have lower than average incomes, and food insecurity is associated with a range of adverse health outcomes amongst young children (Cook and Frank, 2008).

Older people are at greater risk from storms, floods, heat-waves and other extreme events (Brunkard *et al.*, 2008), in part because they tend to be less mobile than younger adults and so find it more difficult to avoid hazardous situations and also because they are more likely to live alone in some cultures. Older people are also more likely to suffer from health conditions that limit the body’s ability to respond to stressors such as heat and air pollution (Gamble *et al.*, 2013).

The relationship between gender and vulnerability is complex. Worldwide, mortality due to natural disasters, including droughts, floods and storms, is higher among women than men (World Health Organization, 2011). However there is variation regionally. In the United States, males are at greater risk of death following flooding (Jonkman and Kelman, 2005). A study of the health effects of flooding in Hunan province, China, also found an excess of flood deaths among males, often related to rural farming (Abuaku *et al.*, 2009). In Canada’s Inuit population males are exposed to dangers associated with insecure sea ice, while females may be more vulnerable to the effects of diminished food supplies (Pearce *et al.*, 2011). In the Paris 2003 heat wave, excess mortality was greater among females overall, but there were more excess deaths among men in the working age span (25 – 64) possibly due to differential exposures to heat in occupational settings (Fouillet *et al.*, 2006). In Bangladesh, females are more affected than males by a range of climate hazards, due to differences in prevalence of poverty, undernutrition and exposure to water-logged environments (Neelormi *et al.*, 2009). The effect of food insecurity on growth and development in childhood may be more damaging for girls than boys (Cook and Frank, 2008).

Pregnancy is a period of increased vulnerability to a wide range of environmental hazards, including extreme heat (Strand *et al.*, 2012) and infectious diseases such as malaria, foodborne infections and influenza (Van Kerkhove *et al.*, 2011).

11.3.4. Socioeconomic Status

The poorest countries and regions are generally most susceptible to damage caused by climate extremes and climate variability (Malik *et al.*, 2012), but wealthy countries are not immune, as shown by the deaths resulting from bushfires in Australia in 2009 (Teague *et al.*, 2010). Also, rapid economic development may increase the risks of climate-related health issues. For instance, changes in Tibet, China including new roads and substantial in-migration may explain (along with above-average warming) the appearance and establishment in Lhasa of *Culex pipiens*, a mosquito capable of transmitting the West Nile virus (Liu *et al.*, 2013b).

A review of global trends in tropical cyclones 1970-2009 found that mortality risk at country-level depended most strongly on three factors: storm intensity, quality of governance, and levels of poverty (Peduzzi *et al.*, 2012). Individuals and households most vulnerable to climate hazards tend to be those with relatively low socioeconomic status (Friel *et al.*, 2008). A study of the impacts of flooding in Bangladesh found that household risk reduced with increases in both average income and number of income sources. Poorer households were not only more severely affected by flooding, but they took preventive action less often, and received assistance after flooding less frequently than did more affluent households (Brouwer *et al.*, 2007).

In many countries, race and ethnicity are powerful markers of health status and social disadvantage. Black Americans have been reported to be more vulnerable to heat-related deaths than other racial groups in the United States (Basu and Ostro, 2008). This may be due to a higher prevalence of chronic conditions such as over-weight and diabetes (Lutsey *et al.*, 2010), financial circumstances (for instance, lower incomes may restrict access to air conditioning during heat-waves) (Ostro *et al.*, 2010), or community-level characteristics such as higher local crime rates or disrupted social networks (Browning *et al.*, 2006). Indigenous peoples who depend heavily on local resources, and live in parts of the world where climates are changing quickly, are generally at greater risk of economic losses and poor health. Studies of the Inuit people, for example, show that rapid warming of the Canadian Arctic is jeopardizing hunting and many other day-to-day activities, with implications for livelihoods and well-being (Ford, 2009).

11.3.5. Public Health and Other Infrastructure

Populations that do not have access to good quality health care and essential public health services are more likely to be adversely affected by climate variability and climate change (Frumkin and McMichael, 2008). Harsh economic conditions in Europe since 2008 led to cutbacks in health services in some countries, followed by a resurgence of climate-sensitive infectious diseases including malaria (Karanikolos *et al.*, 2013). The condition of the physical infrastructure that supports human settlements also influences health risks (this includes supply of power, provision of water for drinking and washing, waste management and sanitation: see Chapter 8). In Cuba, a country with a well-developed public health system, dengue fever has been a persistent problem in the larger cities, due in part to the lack of a constant supply of drinking water in many neighbourhoods (leading to people storing water in containers that are suitable breeding sites for the disease vector, *A. aegypti*) (Bulto *et al.*, 2006). In New York, daily mortality spiked after a city-wide power failure in August 2003, due in part to increased exposure to heat (Weis, 2011).

11.3.6. Projections for Vulnerability

Population growth is linked to climate change vulnerability. If nothing else changes, increasing numbers of people in locations that are already resource-poor and are affected by climate risks will magnify harmful impacts. Virtually all the projected growth in populations will occur in urban agglomerations, mostly in large, low latitude hot countries in which a high proportion of the workforce is deployed outdoors with little protection from heat. About 150 million people currently live in cities affected by chronic water shortages and by 2050, unless there are rapid improvements in urban environments, the number will rise to almost a billion (McDonald *et al.*, 2011). Under a "business as usual" scenario with mid-range population growth, the OECD projects that about 1.4 billion people will be without access to basic sanitation in 2050 (OECD, 2012). The age structure of the population also has implications for vulnerability (see Figure 11-2). The proportion aged over 60, world-wide, is projected to increase from about 10% presently to about 32% by the end of the century (Lutz *et al.*, 2008). The prevalence of overweight and obesity, which is associated with relatively poor heat tolerance, has increased almost everywhere in the last 20 years, and in many countries the trend continues upwards (Finucane *et al.*, 2011). It has been pointed out that the Sahel region of Africa may be particularly vulnerable to climate change because it already suffers so much stress from population pressure, chronic drought, and governmental instability (Diffenbaugh and Giorgi, 2012; Potts and Henderson, 2012).

[INSERT FIGURE 11-2 HERE
Figure 11-2: Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities – who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for 3 different "SRES" scenarios (Blue = B1; Green = A1B, Red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Coloured boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models. Source: World Health Organization and World Meteorological Organization, 2012.]

Future trends in social and economic development are critically important to vulnerability. For instance, countries with a higher Human Development Index (HDI) (a composite of life expectancy, education, literacy and GDP per capita) are less affected by the floods, droughts and cyclones that take place (Patt *et al.*, 2010). Therefore policies that boost health, education, and economic development should reduce future vulnerability. Overall, there have been substantial improvements in HDI in the last 30 years, but this has been accompanied by increasing inequalities between and within countries, and has come at the cost of high consumption of environmental resources (UNDP, 2011).

11.4. Direct Impacts of Climate and Weather on Health

11.4.1. Heat and Cold – Related Impacts

Although there is ample evidence of the effects of weather and climate on health, there are few studies of the impacts of climate change itself. (An example: Bennett *et al* (2013) reported that the ratio of summer to winter deaths in Australia increased between 1968 and 2010, in association with rising annual average temperatures.) The issue is scale, since climate change is defined in decades. Robust studies require not only extremely long-term data series on climate and disease rates, but also information on other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. Wherever risks are identified, health agencies are mandated to intervene immediately, biasing long-term analyses.

Nevertheless, the connection between weather and health impacts is often sufficiently direct to permit strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between hot days (commonly defined in terms of the percentiles of daily maximum temperature for a specified location) and increases in mortality is very robust (Honda *et al*., 2013). The IPCC Special Report on Extreme Events (SREX) concludes that it is *very likely* that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. If there has been an increase in daily maximum temperatures, then it follows, in our view, that the number of heat-related deaths is *likely* to have also increased. For example, Christidis *et al* (2012) concluded that it is "extremely likely (probability greater than 95%)" that anthropogenic climate change at least quadrupled the risk of extreme summer heat events in Europe in the decade 1999-2008. The 2003 heat wave was one such record event: therefore the probability that particular heat wave can be attributed to climate change is 75% or more, and on this basis it is *likely* the excess mortality attributed to the heat wave (about 15,000 deaths in France alone (Fouillet *et al.*, 2008)) was caused by anthropogenic climate change.

The rise in minimum temperatures may have contributed to a decline in deaths associated with cold spells, however the influence of seasonal factors other than temperature on winter mortality suggests that the impacts on health of more frequent heat extremes greatly outweigh benefits of fewer cold days (Ebi and Mills, 2013; Kinney *et al.*, 2012). Quantification, globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and these point to effects of heat, but not cold, on mortality (Hajat *et al.*, 2010). There is also significant uncertainty over the degree of physiological, social or technological adaptation to increasing heat over long time periods.

11.4.1.1. Mechanisms

The basic processes of human thermoregulation are well-understood. If the body temperature rises above 38°C (“heat exhaustion”), physical and cognitive functions are impaired; above 40.6°C (“heat stroke”), risks of organ damage, loss of consciousness, and death increase sharply. Detailed exposure-response relationships were described long ago (Wyndham, 1969), but the relationships in different community settings and for different age/sex groups are not yet well established. The early studies are supported by more recent experimental and field studies (Parsons, 2003; Ramsey and Bernard, 2000) and meta-analysis (Bouchama *et al.*, 2007), that show significant effects of heat stress as body temperatures exceed 40°C, and heightened vulnerability in individuals with pre-existing disease.

At high temperatures, displacement of blood to the surface of the body may lead to circulatory collapse. Indoor thermal conditions, including ventilation, humidity, radiation from walls or ceiling and the presence or absence of air-conditioning are important in determining whether adverse events occur, but these variables are seldom well-measured in epidemiological studies (Anderson *et al.*, 2012). Biological mechanisms are less evident for other causes of death, such as suicide, that are sometimes related to high temperature (Kim *et al.*, 2011; Likhvar *et al.*, 2011; Page *et al.*, 2007).

Heat waves refer to a run of hot days; precisely how many days, and how high the temperatures must rise, are defined variously (Kinney *et al.*, 2008). Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of the short-term temperature mortality relationship (Anderson and Bell, 2011; D'Ippoliti *et al.*, 2010), although the added effect is relatively small in some series, and most evident with prolonged heat waves (Gasparrini and Armstrong, 2011). Because heat waves are relatively infrequent compared with the total number of days with temperatures greater than the optimum for that location, the effects of heat waves are only a fraction of the total impact of heat on health. Some studies have shown larger effects of heat and heat waves earlier in the hot season (Anderson and Bell, 2011; Rocklov *et al.*, 2011). This may be testament to the importance of acclimatisation and adaptive measures, or may result from a large group in the population that is more susceptible to heat early in the season (Rocklov *et al.*, 2009; Rocklov *et al.*, 2011).

The extreme heat wave in Europe in 2003 led to numerous epidemiological studies. Reports from France (Fouillet *et al.*, 2008) concluded that most of the extra deaths occurred in elderly people (80% of those who died were above 75 years). Questions were raised at the time as to why this event had such a devastating effect (Kosatsky, 2005). It is still not clear, but one contributing factor may have been the relatively mild influenza season the year before. Recent studies have found that when the previous year's winter mortality is low, the effect of summer heat is increased (Ha *et al.*, 2011; Rocklov and Forsberg, 2009) because mild winters may leave a higher proportion of vulnerable people (Stafoggia *et al.*, 2009). Most studies of heat have been in high-income countries, but there has been work recently in low- and middle-income countries, suggesting heterogeneity in vulnerability by age groups and socio-economic factors similar to that seen in higher-income settings (Bell *et al.*, 2008; McMichael *et al.*, 2008; Pudpong and Hajat, 2011).

Numerous studies of temperature-related morbidity, based on hospital admissions or emergency presentations, have reported increases in events due to cardio-vascular, respiratory and kidney diseases (Hansen *et al.*, 2008; Knowlton *et al.*, 2009; Lin and Chan, 2009) and the impact has been related to the duration and intensity of heat (Nitschke *et al.*, 2011).

There is evidence now that both average levels and variability in temperature are important influences on human health. The standard deviation of summer temperatures was associated with survival time in a US cohort study of persons aged over 65 years with chronic disease who were tracked from 1985-2006 (Zanobetti *et al.*, 2012). Greater variability was associated with reduced survival. A study that modeled separately projected increases in temperature variability and average temperatures for six cities for 2070-2099 found that, with one exception, variability had an effect (increased deaths) over and above what was estimated from the rise in average temperatures (Gosling *et al.*, 2009). Relevant to 11.5, rapid changes in temperature may also alter the balance between humans and parasites, increasing opportunities for new and resurgent diseases. The speed with which organisms adapt to changes in temperatures is, broadly speaking, a function of mass, and laboratory studies have shown that microbes respond more quickly to a highly variable climate than do their multi-cellular hosts (Raffel *et al.*, 2012).

Health risks during heat extremes are greater in people who are physically active (e.g. manual labourers). This has importance for recreational activity outdoors and it is relevant especially to the impacts of climate change on occupational health (11.6.2) (Ebi and Mills, 2013; Kjellstrom *et al.*, 2009a).

Heat also acts on human health through its effects, in conjunction with low rainfall, on fire risk. In Australia in 2009, record high temperatures, combined with long-term drought, caused fires of unprecedented intensity and 173 deaths from burns and injury (Teague *et al.*, 2010). Smoke from forest fires has been linked elsewhere with increased mortality and morbidity (Analitis *et al.*, 2012) (see 11.5.3.2).

11.4.1.2. Near-Term Future

The climate change scenarios modeled by WG1 project rising temperatures and an increase in frequency and intensity of heat waves (2.6.1 and chapter 1 of this report) in the near-term future, defined as roughly midway through the 21st century, or the era of climate responsibility (see SPM). It is uncertain how much acclimatization may mitigate the effects on human health (Baccini *et al.*, 2011; Bi and Parton, 2008; Hanna *et al.*, 2011; Honda *et al.*, 2013; Maloney and Forbes, 2011; Peng *et al.*, 2011; Wilkinson *et al.*, 2007; Wilkinson *et al.*, 2007). In New York, it was estimated that acclimatization may reduce the impact of added summer heat in the 2050s by roughly a quarter (Knowlton *et al.*, 2007). In Australia, the number of "dangerously hot" days, when core body temperatures may increase by ≥ 2ºC and outdoor activity is hazardous, is projected to rise from the current 4-6 days per year to 33-45 days per year by 2070 (with SRES A1FI) for non-acclimatized people. Among acclimatized people, an increase from 1-5 days per year to 5-14 days per year is expected (Hanna *et al.*, 2011).

For reasons given above, it is not clear whether winter mortality will decrease in a warmer, but more variable, climate (Ebi and Mills, 2013; Kinney *et al.*, 2012). Overall, we conclude that the increase in heat-related mortality by mid-century will outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson *et al.*, 2007). A similar pattern has been projected for temperate zones. A study of three Quebec cities, based on SRES A2 and B2, extended to 2099, showed an increase in summer mortality that clearly outweighed a small reduction in autumn deaths, and only slight variations in winter and spring (Doyon *et al.*, 2008). Another study in Brisbane, Australia, using years of life lost as the outcome, found the gains associated with fewer cold days were less than the losses caused by more hot days, when warming exceeded 2ºC. (Huang *et al.*, 2012). A similar trend is reported in the United Kingdom (Health Protection Agency, 2012) and in New York City (Knowlton *et al.*, 2007).

11.4.2. Floods and Storms

Floods are the most frequently occurring type of natural disaster (Guha-Sapir *et al.*, 2011). In 2011, six of the 10 biggest natural disasters were flood events, when considered in terms of both number affected (112 million people) and number of deaths (3,140 people) (Guha-Sapir *et al.*, 2011). Globally, the frequency of river flood events has been increasing, as well as economic losses, due to the expansion of population and property in flood plains (chapter 18). There is little information on health trends attributable to flooding, except for mortality and there are large differences in mortality risk between countries (UNISDR, 2011). Mortality from flooding and storm events is generally declining, but there is good evidence that mortality risks first increase with economic development before declining (De Haen and Hemrich, 2007; Kellenberg and Mobarak, 2008; Patt *et al.*, 2010). For instance, migration to slums to coastal cities may increase population exposure at a greater pace than can be compensated for by mitigation measures (see chapter 10 on urban risks). Severe damaging floods in Australia in 2010-2011 and in the Northeastern United States in 2012 indicate that high-income countries may still be affected (Guha-Sapir *et al.*, 2011).

11.4.2.1. Mechanisms

Flooding and windstorms adversely affect health through drowning, injuries, hypothermia, infectious diseases (e.g. diarrhoeal disease, leptospirosis, vector-borne disease, cholera) (Jakubicka *et al.*, 2010; Schnitzler *et al.*, 2007). Since AR4, more evidence has emerged on the long term (months-years) implications of flooding for health. Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). The prevalence of mental health symptoms (psychological distress, anxiety and depression) was two to five times higher among individuals who reported flood water in the home compared to non-flooded individuals (2007 flood in England and Wales)(Paranjothy *et al.*, 2011). In the United States, signs of hurricane-related mental illness were observed in a follow-up of New Orleans' residents almost two years after Hurricane Katrina (Kessler *et al.*, 2008).

The attribution of deaths to flood events is complex; most reports of flood deaths include only immediate traumatic deaths, which means that the total mortality burden is under-reported (Health Protection Agency, 2012). There is some uncertainty as to whether flood events are associated with a longer-term (6-12 months) effect on mortality in the flooded population. No persisting effects were observed in a study in England and Wales (Milojevic *et al.*, 2011), but longer-term increases in mortality were found in a rural population in Bangladesh (Milojevic *et al.*, 2012).

11.4.2.2. Near-Term Future

Under most climate change scenarios, it is expected that more frequent intense rainfall events will occur in most parts of the world in the future (IPCC, 2012). If this happens, floods in small catchments will be more frequent, but the consequence is uncertain in larger catchments (See Chapter 3). In terms of exposure, it is expected that more people will be exposed to floods in Asia, Africa and Central and South America (Chapter 3). Also, increases in intense tropical cyclones are *likely* in the late 21st century (WG1 Table SPM.1). It has been estimated conservatively that around 2.8 billion people were affected by floods between 1980-2009, with over 500,000 deaths (Doocy *et al.*, 2013). On this basis we conclude it is *very likely* that health losses caused by storms and floods will increase this century if no adaptation measures are taken. What is not clear is how much of this projected increase can be attributed to climate change. Dasgupta *et al.* (2009) developed a spatially explicit mortality model for 84 developing countries and 577 coastal cities. They modelled 1:100 year storm-surge events, and assessed future impacts under climate change, accounting for sea level rise and a 10% increase in event intensity. In the 84 developing countries, an additional 52 million people and 30,000 km^2 of land were projected to be affected by 2100.

11.4.3. Ultraviolet Radiation

Ambient UV levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers and cataracts in the eye. In one study in the United States, the number of cases of squamous cell carcinoma was 5.5% higher for every 1°C increment in average temperatures, and basal cell carcinoma was 2.9% more common with every 1°C increase. These values correspond to an increase in the effective UV dose of 2% for each 1°C (van der Leun *et al.*, 2008). However, exposure to the sun has beneficial effects on synthesis of Vitamin D, with important consequences for health. Accordingly the balance of gains and losses due to increased UV exposures vary with location, intensity of exposure and other factors (such as diet) that influence Vitamin D levels (Lucas *et al.*, 2013). Studies of stratospheric ozone recovery and climate change project that ultraviolet radiation levels at Earth's surface will generally return to pre-1980 levels by mid-century, and may diminish further by 2100, although there is high uncertainty around the projections (Correa *et al.*, 2013). On the other hand, higher temperatures in countries with temperate climates may result in an increase in the time which people spend outdoors (Belanger *et al.*, 2009) and lead to additional UV-induced adverse effects.

11.5. Ecosystem-Mediated Impacts of Climate Change on Health Outcomes

11.5.1. Vector-Borne and Other Infectious Diseases

Vector-borne diseases (VBDs) refer most commonly to infections transmitted by the bite of blood-sucking arthropods such as mosquitoes or ticks (Wong, Harris, Rodriguez-Galindo, & Johnson, 2013). These are some of the best-studied diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors (Bangs *et al.*, 2006; Bi *et al.*, 2007; Halide and Ridd, 2008; Wu *et al.*, 2009). Table 11-1 summarizes what is known about the influence of weather and climate on selected VBDs.

[INSERT TABLE 11-1 HERE
Table 11-1: The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).]

11.5.1.1. Malaria

Malaria is mainly caused by five distinct species of plasmodium parasite (*Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae, Plasmodium ovale, Plasmodium knowlesi*), transmitted between individuals by Anopheline mosquitoes. In 2010 there were an estimated 216 million episodes of malaria worldwide, mostly amongst children under 5 years in the African Region (World Health Organization, 2010). The number of global malaria deaths was estimated to be 1,238,000 in 2010 (Murray *et al.*, 2012). Worldwide, there have been significant advances made in malaria control in the last 20 years (Feachem, 2011).

The influence of temperature on malaria development appears to be non-linear, and is vector-specific (Alonso *et al.*, 2011). Increased variations in temperature, when the maximum is close to the upper limit for vector and pathogen, tend to reduce transmission, while increased variations of mean daily temperature near the minimum boundary increase transmission (Paaijmans *et al.*, 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *A. funestus* in Kenya found that abundance, distribution, and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope *et al.*, 2009). There are lag-times according to the lifecycle of the vector and the parasite: a study in central China reported that malaria incidence was related to the average monthly temperature, the average temperature of the previous two months, and the average rainfall of the current month (Zhang *et al.*, 2012).

More work has been done since AR4 to elucidate the role of local warming on malaria transmission in the East African highlands, but this is hampered by the lack of time series data on levels of drug resistance and intensity of vector control programs. Earlier research had failed to find a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer periods have confirmed increasing temperatures since 1979 (Omumbo *et al.*, 2011; Stern *et al.*, 2011). The strongly non-linear response to temperature means that even modest warming may drive large increases in transmission of malaria, if conditions are otherwise suitable (Alonso *et al.*, 2011; Pascual *et al.*, 2006). On the other hand, at relatively high temperatures modest warming may reduce the potential of malaria transmission (Lunde *et al.*, 2013). One review (Chaves and Koenraadt, 2010) concluded that decadal temperature changes have played a role in changing malaria incidence in East Africa. But malaria is very sensitive also to socioeconomic factors and health interventions, and the generally more conducive climate conditions have been offset by more effective disease control activities. The incidence of malaria has reduced over much of East Africa (Stern *et al.*, 2011) although increased variability in disease rates has been observed in some high altitude areas (Chaves *et al.*, 2012).

At the global level, economic development and control interventions have dominated changes in the extent and endemicity of malaria over the last 100 years (Gething *et al.*, 2010). Although modest warming has facilitated malaria transmission (Alonso *et al.*, 2011; Pascual *et al.*, 2006), the proportion of the world's population affected by the disease has been reduced, largely due to control of *P. vivax* malaria in moderate climates with low transmission intensity. However, the burden of disease is still high and may actually be on the increase again, in some locations (World Health Organization, 2012). For instance, locally-transmitted malaria has re-emerged in Greece in association with economic hardship and cutbacks in government spending (Andriopoulos *et al.*, 2013; Danis *et al.*, 2011).

11.5.1.2. Dengue Fever

Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years (World Health Organization, 2013). Each year there occur about 390 million dengue infections worldwide, of which roughly 96 million manifest with symptoms (Bhatt *et al.*, 2013). Three quarters of the people exposed to dengue are in the Asia-Pacific region, but many other regions are affected also. The first sustained transmission of dengue in Europe since the 1920s was reported in 2012 in Madeira, Portugal (Sousa *et al.*, 2012). The disease is associated with climate on spatial (Beebe *et al.*, 2009; Li *et al.*, 2011; Russell *et al.*, 2009), temporal (Descloux *et al.*, 2012; Earnest *et al.*, 2012; Gharbi *et al.*, 2011; Herrera-Martinez and Rodriguez-Morales, 2010; Hii *et al.*, 2009; Hsieh and Chen, 2009; Pham *et al.*, 2011) and spatiotemporal (Chowell *et al.*, 2008; Chowell *et al.*, 2011; Lai, 2011) scales.

The principal vectors for dengue, *Aedes aegypti* and *Ae. albopictus*, are climate-sensitive. Over the last two decades, climate conditions have become more suitable for *albopictus* in some areas (e.g. over central northwestern Europe) but less suitable elsewhere (e.g. over southern Spain) (Caminade *et al.*, 2012). Distribution of *Ae. albopictus* in northwestern China is highly correlated with annual temperature and precipitation (Wu *et al.*, 2011). Temperature, humidity and rainfall are positively associated with dengue incidence in Guangzhou, China, and wind velocity is inversely associated with rates of the disease (Li *et al.*, 2011; Lu and Lin, 2009). Several studies in Taiwan reported that typhoons remain an important factor affecting vector population and dengue fever (Hsieh and Chen, 2009; Lai, 2011). Typhoons result in extreme rainfall, high humidity and water pooling, and may generate fresh mosquito breeding sites. A study in Dhaka, Bangladesh reported increased rates of admissions to hospital due to dengue with both high and low river levels (Hashizume and Dewan, 2012). In some circumstances, it is apparent that heavy precipitation favors the spread of dengue fever, but drought can also be a cause if households store water in containers that provide suitable mosquito breeding sites (Beebe *et al.*, 2009; Padmanabha *et al.*, 2010).

_____ START BOX 11-2 HERE _____

Box 11-2. Case Study: An Intervention to Control Dengue Fever

Seasonality in dengue transmission is well established in many parts of the world, and transmission occurs mostly during the wettest months of the year (Chadee *et al.*, 2007; Gubler and Kuno, 1997). Figure 11-3 shows that about 80% of dengue fever cases in Trinidad were recorded during the wet season, a period when the *Ae. aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control program that concentrated on reducing the mosquito population before the onset of the rains, by application of insecticides (temephos) into the water drums that serve as primary breeding sites of *Ae. aegypti* in the

Caribbean. The one-off treatment effectively controlled the mosquito populations for almost 12 weeks after which the numbers reverted to levels observed in the untreated control areas.

[INSERT FIGURE 11-3 HERE
Figure 11-3: a) Rainfall, temperature, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002-2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined “dengue season” between June and November over two years of the study. Source: (Chadee *et al.*, 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission. Source: Chadee, 2009.]

Climate scenarios that extend to 2071-2100 project changes in the intensity and frequency of rainfall events in the Caribbean (Campbell *et al.*, 2011). In these scenarios, there is greater variability in rainfall patterns during November to January, with the northern Caribbean region receiving more rainfall than in the southern Caribbean (Campbell *et al.*, 2011). There may be water shortages during drought periods, and flooding after episodes of heavy rainfall, both of which affect the breeding habitats of *Ae. aegypti* and *Ae. albopictus*. Vector control strategies will need to be planned and managed astutely to systematically reduce mosquito populations.

_____ END BOX 11-2 HERE _____

11.5.1.3. Tick-Borne Diseases

Tick-borne encephalitis (TBE) is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Lyme disease is an acute infectious disease caused by the spirochaete bacteria *Borrelia burgdorferi* and is reported in Europe, the USA and Canada. *Borrelia* is transmitted to humans by the bite of infected ticks belonging to a few species of the genus *Ixodes* ("hard ticks"). Many studies have reported associations between climate and tick-borne diseases (Andreassen *et al.*, 2012; Estrada-Peña *et al.*, 2012; Jaenson *et al.*, 2012; Lukan *et al.*, 2010; Okuthe and Buyu, 2006; Tokarevich *et al.*, 2011).

In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996-2004 based on an analysis of active and passive surveillance data (Ogden *et al.*, 2010). However, there is no evidence so far of any associated changes in the distribution in North America of human cases of tick-borne diseases.

There was a marked rise in TBE cases from the 1970s in central and eastern Europe. Spring-time daily maximum temperatures rose in the late 1980s, sufficient to encourage transmission of the TBE virus. For instance, in the Czech Republic, between 1970 and 2008, there were signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz *et al.*, 2012). However variations in illness rates across the region demonstrate that climate change alone cannot explain the increase. Socioeconomic changes (including changes in agriculture and recreational activities) have affected patterns of disease in Europe (Randolph, 2010; Sumilo *et al.*, 2008). The complex ecology of tick-borne diseases such as Lyme disease and TBE make it difficult to attribute particular changes in disease frequency and distribution to specific environmental factors such as climate (Gray *et al.*, 2009).

11.5.1.4. Other Vector-Borne Diseases

Hemorrhagic fever with renal syndrome (HFRS) is a zoonosis caused by the Hanta virus, and leads to approximately 200,000 hospitalized cases each year. The incidence of this disease has been associated with temperature, precipitation, and relative humidity (Fang *et al.*, 2010; Liu *et al.*, 2011; Pettersson *et al.*, 2008). Plague, one of the oldest diseases known to humanity, persists in many parts of the world. Outbreaks have been linked to seasonal and inter-annual variability in climate (Holt *et al.*, 2009; MacMillan *et al.*, 2012; Nakazawa *et al.*, 2007; Stenseth *et al.*, 2006; Xu *et al.*, 2011). Chikungunya fever is a climate-sensitive mosquito-transmitted viral disease (Anyamba *et al.*, 2012), first identified in Africa, now present also in Asia, and the disease has recently emerged in parts of Europe (Angelini *et al.*, 2008). The incidence in China of Japanese encephalitis, another mosquito-borne viral disease, is correlated with temperature and rainfall, especially during the warmer months of the year (Bai *et al.*, 2013). In West Africa, outbreaks of Rift Valley Fever, an acute viral disease affecting humans and domestic animals, are linked to within-season variability in rainfall (Caminade *et al.*, 2011).

11.5.1.5. Near-Term Future

Using the A1B climate change scenario, Béguin *et al.* (2011) projected the population at risk of malaria to 2030 and 2050. With GDP *per capita* held constant at 2010 values, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. Keeping climate constant, and assuming strong economic growth allied with social development ("best case"), the model projected 1.74 billion people at risk (approximately half the present number at risk) in 2050. Factoring in climate change would increase the "best case" estimate of the number of people at risk of malaria in 2050 to 1.95 billion, which is 200 million more than if disease control efforts were not opposed by higher temperatures and shifts in rainfall patterns.

There are no recent studies that project the return of established malaria to North America or Europe, where it was once prevalent. However suitable vectors for *P. vivax* malaria abound in these parts of the world, and recent experience in southern Europe demonstrates how rapidly the disease may re-appear if health services falter (Bonovas and Nikolopoulos, 2012).

A systematic review of research on the distribution of dengue and possible influence of climate change (Van Kleef *et al.*, 2010) concluded that the area of the planet that was climatically suitable for dengue would increase under most scenarios, but it was not possible to project the impact on disease incidence. Åström (Astrom *et al.*, 2012) estimated the population at risk out to the year 2050. The study was based on routine disease reports, surveys, population projections, estimates of GDP growth and the A1B scenario for climate change. Assuming high GDP growth that benefits all populations, the number exposed to dengue in 2050 falls to 4.46 billion, i.e. the adverse effects of climate change are balanced by the beneficial outcomes of development. This study considered only the margins of the geographic distribution of dengue (where economic development has its strongest effect) and did not examine changes in intensity of transmission in areas where the disease is already established.

Kearny (2009) used biophysical models to examine the potential extension of vector range in Australia. He predicted that climate change would increase habitat suitability throughout much of Australia. Changes in water storage as a response to a drier climate may be an indirect pathway, through which climate change affects mosquito breeding (Beebe *et al.*, 2009).

11.5.2. Food- and Water-Borne Infections

Human exposure to climate-sensitive pathogens occurs by ingestion of contaminated water or food, incidental ingestion during swimming or by direct contact with eyes, ears or open wounds. Pathogens in water may be zoonotic in origin, concentrated by bivalve shellfish (e.g., oysters) or deposited on irrigated food crops. Pathogens of concern include enteric organisms that are transmitted by the fecal oral route and also bacteria and protozoa that occur naturally in aquatic systems. Climate may act directly by influencing growth, survival, persistence, transmission or virulence of pathogens; indirect influences include climate-related perturbations in local ecosystems or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrios

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Cholera may be transmitted by drinking water or by environmental exposure in seawater and seafood; other Vibrio species are solely linked to seawater and shellfish. These include *V. parahaemolyticus* and *V. vulnificus*, with *V. alginolyticus* emerging in importance (Weis, 2011). Risk of infection is influenced by temperature, precipitation and accompanying changes in salinity due to freshwater run-off, addition of organic carbon or other nutrients or changes in pH. These factors all affect the spatial and temporal range of the organism and also influence exposure routes (e.g. direct contact or via seafood). In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (Islam, 2009; Paz, 2009; Reyburn *et al.*, 2011). In addition, heavy rainfall promotes the transmission of pathogens when there is not secure disposal of fecal waste. An unequivocal positive relationship between Vibrio numbers and SST in the North Sea has been established by DNA analyses of formalin-fixed samples collected over a 44 year period (Vezzulli *et al.*, 2012). Cholera outbreaks have been linked to variations in temperature and rainfall, and other variables including sea and river levels, sea chlorophyll and cyanobacteria contents, Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO) events (Bompangue *et al.*, 2011; Constantin de Magny *et al.*, 2008; Hashizume, 2008; Reyburn *et al.*, 2011; Rinaldo *et al.*, 2012).

11.5.2.2. Other Parasites, Bacteria, and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011). Mostly, however, the specific causes of the diarrheal illness are not known, nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, among the most common zoonotic food and waterborne bacterial pathogens worldwide, which both show distinct seasonality in infection and higher disease rates at warmer temperatures. The association between climate (especially temperature) and non-outbreak ('sporadic') cases of salmonellosis may, in part, explain seasonal and latitudinal trends in diarrhea (Lake, 2009).

Among the enteric viruses, there are distinct seasonal patterns in infection that can be related indirectly to temperature. Enterovirus infections in the U.S. peak in summer and fall months (Khetsuriani *et al.*, 2006). After controlling for seasonality and interannual variations, hand, foot and mouth disease (caused by coxsackievirus A16 and enterovirus 71), shows a linear relationship with temperature in Singapore, with a rapid rise in incidence when the temperature exceeds 32°C (Hii *et al.*, 2011). However, it is not clear what the underlying driver is and if temperature is confounded by other seasonal factors.

Temperature is directly linked with risk of enteric disease in Arctic communities, since melt of the permafrost hastens transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources or other surface waters (Martin *et al.*, 2007). Additionally, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008).

Rainfall has also been associated with enteric infections. Bacterial pathogens are more likely to grow on produce crops (e.g. lettuce) in simulations of warmer conditions (Liu *et al.*, 2013a), and become attached to leafy crops under conditions of both flooding and drought (Ge *et al.*, 2012). This latter pattern is reflected in patterns of illness (Bandyopadhyay *et al.*, 2012). Higher concentrations of enteric viruses have been reported frequently in drinking water and recreational water following heavy rainfall (Delpla *et al.*, 2009).

Worldwide, rotavirus infections caused about 450,000 deaths in children under 5 years old in 2008 (Tate *et al.*, 2012). There are seasonal peaks in the number of cases in temperate and subtropical regions but less distinct patterns are seen within 10° latitude of the equator (Cook *et al.*, 1990). Variations in the timing of peak outbreaks between countries or regions (Atchison *et al.*, 2010; Turcios *et al.*, 2006) and variations with time in the same country (Dey *et al.*, 2010) have been attributed to fluctuations in the number and seasonality of births (Pitzer *et al.*, 2009; Pitzer *et al.*, 2011). While vaccination against rotavirus is expected to reduce the total burden of disease, it may also increase seasonal variation (Pitzer *et al.*, 2011; Tate *et al.*, 2009).

Harmful algal blooms can be formed by (i) dinoflagellates that cause outbreaks of paralytic shellfish poisoning, ciguatera fish poisoning and neurotoxic shellfish poisoning; (ii) cyanobacteria that produce toxins causing liver, neurological, digestive and skin diseases; and (iii) diatoms that can produce domoic acid, a potent neurotoxin which is bioaccumulated in shellfish and finfish (Erdner *et al.*, 2008). Increasing temperatures promote bloom formation in both fresh water (Paerl *et al.*, 2011), and marine environments (Marques *et al.*, 2010). (See Chapter 5.) Increasing temperature favoured growth of toxic over non-toxic strains of *Microcystis* in lakes in the USA (Davis *et al.*, 2009). Projections of toxin-producing blooms in Puget Sound using an A1B scenario suggest that by the end of the century the "at risk" period may begin 2 months earlier and last up to 1 month longer than at present (Moore *et al.*, 2011).

11.5.2.3. Near-Term Future

Kolstad and Johansson (2011) projected an increase of 8-11% in the risk of diarrhea in the tropics and subtropics in 2039 due to climate change, using the A1B scenario and 19 coupled atmosphere-ocean climate models from CMIP3. This study did not account for future changes in economic growth and social development. Application of down-scaled climate change models showed that overflows of sewage into Chicago's watersheds would increase by 50-120% by 2100, as a result of more frequent and intense rainfall (Patz *et al.*, 2008). In Botswana, if hot, dry conditions begin earlier in the year, and are prolonged, as projected by down-scaled climate scenarios, the present dry season peak in diarrhoeal disease may be amplified (Alexander *et al.*, 2013). However the same analysis projected that incidence of diarrhoeal disease in the wet season would decline.

Zhou *et al.* (2008) studied the effect of climate on transmission of schistosomiasis due to *S. japonicum* in China. They concluded that an additional 784 thousand km^2 would become suitable for schistosomiasis transmission in China by 2050, as the mid-winter freezing line moves northwards (Figure 11-4).

[INSERT FIGURE 11-4 HERE
Figure 11-4: Effect of rising temperatures on the area in which transmission of *Schistosomiasis japonica* may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000. Adapted from Zhou *et al.*, 2008.]

Mangal *et al*. (2008) constructed a mechanistic model of the transmission cycle of another species, *S. mansoni,* and reported a peak in the worm burden in humans at an ambient temperature of 30°C, falling sharply as temperature rises to 35°C. The authors attribute this to the increasing mortality of both the snails and the water-borne intermediate forms of the parasite, and noted that worm burden is not directly linked to the prevalence of schistosomiasis.

11.5.3. Air Quality

Nearly all the non-CO_2 climate-altering pollutants (CAPs – see Chapters 7 and 8 of WGI) are health damaging, either directly or by contributing to secondary pollutants in the atmosphere. Thus, like the ocean acidification and ecosystem/ agriculture fertilization impacts of CO_2, the other CAPs have non-climate-mediated impacts, particularly on health. Although not reviewed in detail in this assessment, the health impacts of non-CO_2 CAPs are substantial globally. See Box 11-3.

_____ START BOX 11-3 HERE _____

Box 11-3. Health and Economic Impacts of Climate-Altering Pollutants (CAPs) Other than CO_2

Although other estimates of the global health impacts of human exposures to particle and ozone pollution have been published in recent years (e.g. (UNEP, 2011)), the most comprehensive was the Comparative Risk Assessment carried out as part of the 2010 Global Burden of Disease Project (Lim *et al.*, 2012). It found that the combined health impact of the household exposures to particle air pollution from poor combustion of solid cooking fuels, plus general ambient pollution, was about 6.8 million premature deaths annually, with about 5 percent overlapping, i.e., coming from the contribution to general ambient pollution of household fuels. It also found that about 150 thousand premature deaths could be attributed to ambient ozone pollution. Put into terms of disability-adjusted life years

(DALYs), particle air pollution was responsible for about 190 million lost DALYs in 2010, or about 7.6% of all DALYs lost. This burden puts particle air pollution among the largest risk factors globally, far higher than any other environmental risk and rivaling or exceeding all of the five dozen risk factors examined, including malnutrition, smoking, high blood pressure, and alcohol.

The economic impact of this burden is difficult to assess as evaluation methods vary dramatically in the literature. Most in the health field prefer to consider some version of a lost healthy life year as the best metric although the economics literature often uses willingness to pay for avoiding a lost life (Jamison *et al.*, 2006). Another difficulty is that any valuation technique that weights the economic loss according to local incomes per capita will value health effects in rich countries more than in poor countries, which would seem to violate some of the premises of a global assessment; see WGIII Chpt 3 for more discussion. Here, however, we will use the mean global income per capita (~ USD 10,000 in 2010) to scope out the scale of the impact globally without attempting to be specific by country or region.

The WHO CHOICE approach for evaluating what should be spent on health interventions indicates that one annual per capita income per DALY is a reasonable upper bound (World Health Organization, 2009a). This would imply that the total lost economic value from global climate-altering pollutants in the form of particles is roughly USD 1.9 trillion, in the sense that the world ought to be willing to pay this much to reduce it. This is about 2.7% of the global economy (approximately USD 70 trillion in 2010).

On the one hand, this shows that global atmospheric pollution already has a major impact on the health and economic well-being of humanity today, due mainly to the direct effects rather than those mediated through climate. If CO_2 is not controlled and climate change continues to intensify while air pollutant controls become more stringent, the climate impacts will become more prominent. The quite different time scales for the two types of impacts make comparisons difficult, however.

Air pollution reductions do not always promote the twin goals of protecting health and climate but can pose trade-offs. All particles are dangerous for health, for example, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith *et al.*, 2009). Indeed elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate (WG1, Fig TS-6). As discussed in the co-benefits section below (11.9), there are nevertheless specific actions that will work toward both goals.

_____ END BOX 11-3 HERE _____

Although there is a large body of literature on the health effects of particulate air pollution (see Box 11-3), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way (WG1, 11.3.5; Annex II). Thus, we focus here on chronic ozone exposures, which are found by WGI to be enhanced in some, but not all, scenarios of future climate change (WG1, TS.5.4.8).

11.5.3.1. Long-Term Outdoor Ozone Exposures

Tropospheric ozone is formed through photochemical reactions that involve nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures (WG1, Ch 8). Therefore, if temperatures rise, many air pollution models (Chang *et al.*, 2010; Ebi and McGregor, 2008; Polvani *et al.*, 2011; Tsai *et al.*, 2008) project increased ozone production especially within and surrounding urban areas (Hesterberg *et al.*, 2009). Enhanced temperature also accelerates destruction of ozone, and the net direct impact of climate change on ozone concentrations worldwide is thought to be a reduction (WG1 TS.5.4.8). Some WG1 (TS.5.4.8) scenarios, however, indicate tropospheric ozone may rise from additional methane emissions stimulated by climate change. Models also show that local variations can have a different sign to the global one (Selin *et al.*, 2009).

Even small increases in atmospheric concentrations of ground-level ozone may affect health (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). For instance, Bell *et al*. (2006) found that levels that meet the US EPA 8-

hour regulation (0.08 ppm over 8 hours) were associated with increased risk of premature mortality. There is a lack of association between ozone and premature mortality only at very low concentrations (from 0 to ~10 ppb) but the association becomes positive and approximately linear at higher concentrations (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). In an analysis of 66 United States cities with 18 years of follow-up (1982-2000), tropospheric ozone levels were found to be significantly associated with cardiopulmonary mortality (Smith *et al.*, 2009). See also the global review by WHO, which includes data from developing countries (World Health Organization, 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which occur more commonly following heat waves and drought, release particulate matter and other toxic substances that may affect large numbers of people for days to months (Finlay *et al.*, 2012; Handmer *et al.*, 2012). During a fire near Denver (USA) in June 2009, 1-hour concentrations of PM_{10} and $PM_{2.5}$ reached 370 µg/m^3 and 200 µg/m^3, and 24-hour average concentrations reached 91 µg/m^3 and 44 µg/m^3, compared to the 24-hour WHO air quality guidelines for these pollutants of 50 µg/m^3 and 25 µg/m^3, respectively (Vedal and Dutton, 2006). One study of worldwide premature mortality attributable to air pollution from forest fires estimated there were 339,000 deaths per year (range 260,000 to 600,000) (Johnston *et al.*, 2012). The regions most affected are Sub-Saharan Africa and Southeast Asia (Johnston *et al.*, 2012).

Extremely high levels of PM_{10} were observed in Moscow due to forest fires caused by a heat wave in 2010. Daily mean temperatures in Moscow exceeded the respective long-term averages by 5°C or more for 45 days. Ten new temperature records were established in July and nine in August, based on measurements since 1885, and an anti-cyclone in the Moscow region prevented dispersion of air pollutants. The highest 24-h pollution levels recorded in Moscow during these conditions were between 430 and 900 µg/m^3 PM_{10} most days, but occasionally reached 1500 µg/m^3. The highest 24-h CO concentration was 30 mg/m^3 compared to the WHO AQG of 7 µg/m^3, and the levels of formaldehyde, ethyl benzene, benzene, toluene and styrene were also increased (State Environmental Institution "Mosecomonitoring", 2010).

There may be an interaction of tropospheric ozone and heat waves. Dear *et al*. (2005) modeled the daily mortality due to heat and exposure to ozone during the European summer heat wave of 2003 and found that possibly 50% of the deaths could have been associated with ozone exposure rather than the heat itself.

11.5.3.3. Aeroallergens

Allergic diseases are common and are climate-sensitive. Warmer conditions generally favour the production and release of air-borne allergens (such as fungi and lower plant spores and pollen) and, consequently, there may be an effect on asthma and other allergic respiratory diseases, such as asthma and allergic rhinitis, as well as effects on conjunctivitis and dermatitis (Beggs, 2010). Children are particularly susceptible to most allergic diseases (Schmier and Ebi, 2009). Increased release of allergens may be amplified if higher CO_2 levels stimulate plant growth. Visual monitoring and experiments have shown that increases in air temperature cause earlier flowering of prairie tallgrass (Sherry *et al.*, 2007). Droughts and high winds may produce windborne dust and other atmospheric materials, which contain pollen and spores, and transport these allergens to new regions.

Studies have shown that increasing concentrations of grass pollen lead to more frequent ambulance calls due to asthma symptoms, with a time lag of 3-5 days (Heguy *et al.*, 2008). Pollen levels have also been linked to hospital visits with rhinitis symptoms (Breton *et al.*, 2006). A cross-sectional study in the three climatic regions of Spain documented a positive correlation between the rate of child eczema and humidity, and negative correlation between child eczema and air temperature or the number of sunshine hours (Suarez-Varela *et al.*, 2008).

11.5.3.4. Near-Term Future

It is projected by WGI that climate change could affect future air quality, including levels of photochemical oxidants and, with much less certainty, fine particles ($PM_{2.5}$). If this occurs, there will be consequences for human health (Bell *et al.*, 2007; Chang *et al.*, 2012; Dong *et al.*, 2011; Lepeule *et al.*, 2012; Meister *et al.*, 2012; West *et al.*, 2013). High temperatures may also magnify the effects of ozone (Jackson *et al.*, 2010; Ren *et al.*, 2008). Increasing urbanization, use of solid biomass fuels, and industrial development in the absence of emission controls could also lead to increases in ozone chemical precursors (Selin *et al.*, 2009; Wilkinson *et al.*, 2009).

Most post-2006 studies on the projected impacts of future climate change on air pollution-related morbidity and mortality have focused on ozone in Europe, the U.S. and Canada (see Table 11-S1; (Bell *et al.*, 2007; Selin *et al.*, 2009; Tagaris *et al.*, 2009)). Projections are rare for other areas of the world, notably the developing countries where air pollution is presently a serious problem and is expected to worsen unless controls are strengthened.

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Jackson *et al.*, 2010; Ren *et al.*, 2008). In general, all-cause mortality related to ozone is expected to increase in the US and Canada (Bell *et al.*, 2007; Cheng *et al.*, 2011; Jackson *et al.*, 2010; Tagaris *et al.*, 2009). Under a scenario in which present air quality legislation is rolled out everywhere, premature deaths due to ozone would be wound back in Africa, South Asia and East Asia. Under a maximum feasible CO_2 reduction scenario related to A2, it is projected that 460,000 premature ozone-related deaths could be avoided in 2030, mostly in South Asia (West *et al.*, 2007). All-cause mortality, however, is not the best metric for comparing air pollution health impacts across regions; given that background disease conditions vary so widely. HIV deaths and malaria deaths, which are prominent in Sub-Saharan Africa, for example, are not expected to increase from air pollution exposures in the same way as deaths from cardiovascular disease that dominate other regions.

A study that investigated regional air quality in the United States in 2050, using a down-scaled climate model (Goddard Institute for Space Studies, Global Climate Model), concluded there would be about 4000 additional annual premature deaths due to increased exposures to $PM_{2.5}$ (Tagaris *et al.*, 2009). Air pollutant-related mortality increases are also projected for Canada, but in this case they are largely driven by the effects of ozone (Cheng *et al.*, 2011). On the basis of the relation of asthma to air quality in the last decade (1999-2010), Thompson *et al*. (2012) anticipate that the prevalence of asthma in South Africa will increase substantially by 2050. Sheffield *et al*. (2011), applying the SRES A2 scenario, projected a median 7.3% increase in summer ozone-related asthma emergency department visits for children (0-17 years) across New York City by the 2020s compared to the 1990s.

11.6. Health Impacts Heavily Mediated through Human Institutions

11.6.1. Nutrition

Nutrition is a function of agricultural production (net of post-harvest wastes and storage losses), socioeconomic factors, such as food prices and access, and human diseases, especially those which affect appetite, nutrient absorption and catabolism (Black *et al.*, 2008; Lloyd *et al.*, 2011). All three may be influenced by climate but only agricultural production has been modeled in a climate impacts framework. Here we use the terms *undernutrition*, which is a health outcome, and *undernourishment*, which reflects national (post-trade) calories available for human consumption, and is expressed as estimated percent of the population receiving ‘insufficient’ calories. We do not use the term “malnutrition,” as it includes overnutrition, which is not considered here (except under co-benefits in 11.9). Undernutrition can be chronic, leading to stunting (low height for age) or acute, leading to wasting (low weight for height); underweight (low weight for age) is a combination of chronic and acute undernutrition.

11.6.1.1. Mechanisms

The processes through which climate change can affect human nutrition are complex (see chapter 7.2.2). Higher temperatures and changes in precipitation may reduce both the quantity and quality of food harvested (e.g. (Battisti and Naylor, 2009)). Lobell *et al*. (2011b) showed for African maize that for each degree above 30°C, yields decreased by 1% under optimal rainfall conditions and by 1.7 % under drought conditions. From their systematic review of more than a thousand studies, Knox *et al*. (2012) drew the conclusion that “climate change is a threat to crop productivity in areas that are already food insecure.” Grace *et al*. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability as well as child stunting in Kenya. The authors conclude that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology. Rising temperatures may also affect food security through the impact of heat on productivity of farmers (see 11.6.2).

The magnitude of detected and predicted decline in land-based agricultural production due to increasing temperatures and changes in rainfall must be put in perspective to other changes, such as increase in harvests due to improved farming knowledge and technology, the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished or wasted in other ways (Foley *et al.*, 2011). There is good evidence that local food price increases have negative effects on food consumption, and therefore on health (Green *et al.*, 2013). Against this background, the global food price fluctuates, though with a recently rising trend. While the main driver is higher energy costs, amplified by speculation (Piesse and Thirtle, 2009), there is growing evidence (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011) and heat waves, may have contributed to higher prices. All else being equal, higher prices increase the number of malnourished people. See Chapter 7 for a more detailed discussion of the impact of climate change on food production.

11.6.1.2. Near-Term Future

Since AR4 at least four studies have been published which project the effect of climate change on undernourishment and undernutrition.

Nelson *et al*. (2010; 2009) conducted two studies using a crop simulation model (DSSAT) and a global agricultural trade model (IMPACT 2009) to estimate crop production (with and without CO_2 enrichment), calorie availability, child underweight, and adaptation costs. The first study (Nelson *et al.*, 2009) was carried out under the A2 emission scenario, using two GCMs (NCAR, CSIRO) and relative to a ‘no climate change’ future. The authors found that yields of most important crops would decline in developing countries by 2050, that per capita calorie availability would drop below levels that applied in the year 2000, and that child underweight would be ~20% higher (in the absence of carbon enrichment effects). That is, about 25 million children would be affected. (See Table 11-2). Of note, the underweight estimates do not account for possible improvements in socioeconomic conditions between 2000 and 2050. However it was estimated that substantial improvements would be necessary to counteract the effects of climate change. These included a 60% increase in yield growth (all crops) over baseline, 30% faster growth in animal numbers, and a 25% increase in the rate of expansion of irrigated areas. The second study by Nelson *et al.* used a wider range of socioeconomic and climate scenarios but health impacts were similar to the first study. Estimates of improved socioeconomic conditions were insufficient to fully offset the potential impacts of climate change: child underweight was estimated to be ~10% higher with climate change compared to a future without climate change.

[INSERT TABLE 11-2 HERE
Table 11-2: Number of under-nourished children less than 5 years of age (in millions) in 2000 and 2050, using the NCAR (National Center for Atmospheric Research) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers’ productivity, and no CO_2 fertilization benefits. Adapted from (Nelson *et al.*, 2009).]

Lloyd *et al.* (2011) built a model for estimating future stunting driven by two principle inputs: estimates of undernourishment (i.e. ‘food-related’ causes of stunting) and socioeconomic conditions (i.e. ‘non-food related’ causes of stunting). The former were based on calorie availability estimates from Nelson *et al*. (2009), and the latter on GDP *per capita* projections and estimates of the Gini index for income distribution. They estimated that by 2050, under A2 emissions with moderate to high economic growth and compared to a future without climate change, there may be a relative increase of severe stunting of 31% to 55% across regions of Sub-Saharan Africa and 61% in South Asia. It should be noted here that severe stunting carries 3 to 4 times the mortality risk of moderate stunting. In a future without climate change, undernutrition was projected to decline, leading the authors to conclude that climate change would hold back efforts to reduce child undernutrition in the most severely affected parts of the world, even after accounting for the potential benefits of economic growth.

In addition to global studies, regional projections of the impacts of climate change on undernutrition have also been carried out since AR4. Grace *et al*. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability as well as child stunting in Kenya. The authors conclude that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology.

Similarly, Jankowska *et al*. (Jankowska *et al.*, 2012) included climate, livelihood and health variables (stunting and underweight). The authors identified a link between type of livelihood and risk of undernutrition, and climate and stunting. Applying the model to Mali, the authors projected impacts to 2025 and estimated that nearly 6 million people may experience undernutrition due to changes in climate, livelihood and demography; three-quarter to one million of this number will be children under five.

In summary, we conclude that climate change will have a substantial negative impact on (i) per capita calorie availability, (ii) childhood undernutrition, particularly stunting and (iii) on undernutrition–related child deaths and DALYs lost in developing countries (high confidence).

11.6.2. Occupational Health

Since AR4, much has been written on the effects of heat on working people (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2009a) and on other climate-related occupational health risks (Bennett and McMichael, 2010; Schulte and Chun, 2009).

11.6.2.1. Heat Strain and Heat Stroke

Worldwide, more than half of all non-household labor-hours occur outdoors, mainly in agriculture and construction (International Fund for Agricultural Development, 2010; International Labor Organization, 2013). Individuals who are obliged to work outside in hot conditions, without access to shade, or sufficient water, are at heightened risk of heat-strain (ICD code T.67, “heat exhaustion”) and heat stroke. Health risks increase with the level of physical exertion. Agricultural and construction workers in tropical developing countries are therefore among the most exposed, but heat stress is also an issue for those working indoors in environments that are not temperature-controlled, and even for some workers in high-income countries such as the USA (Luginbuhl *et al.*, 2008). (See Figure 11-5). Moreover, at higher temperatures there is potential conflict between health protection and economic productivity (Kjellstrom *et al.*, 2011): as workers take longer rests to prevent heat stress, hourly productivity goes down (Sahu *et al.*, 2013).

[INSERT FIGURE 11-5 HERE
Figure 11-5: The 1980-2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Standard Organization standard (1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that Tmax goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health. Source: Lemke and Kjellstrom, 2012.]

11.6.2.2. Heat Exhaustion and Work Capacity Loss

There are international standards of maximum recommended workplace heat exposure and hourly rest time (e.g. (ISO, 1989; Parsons, 2003)) for both acclimatized and non-acclimatized people. In hot countries during the hot season, large proportions of the workforce are affected by heat, and the economic impacts of reduced work capacity may be sufficient to jeopardize livelihoods (Kjellstrom *et al.*, 2011; Kjellstrom *et al.*, 2009a; Kjellstrom and Crowe, 2011; Lecocq and Shalizi, 2007). Kjellstrom and Crow (2011) and Dunne *et al*. (Dunne *et al.*, 2013) report that loss of work productivity during the hottest and wettest seasons has already occurred, at least in Asia and Africa.

11.6.2.3. Other Occupational Health Concerns

In areas where vector-borne diseases, such as malaria and dengue fever, are common, people working in fields without effective protection may experience a higher incidence of these diseases when climatic conditions favour mosquito breeding and biting (Bennett and McMichael, 2010). Increasing heat exposure in farm fields during the middle of the day may lead to more work during dawn and dusk when some of the vectors are biting humans more actively. Exposure to heat affects psychomotor, perceptual, and cognitive performance (Hancock *et al.*, 2007) and increases risk of injuries (Ramsey, 1995). Extreme weather events and climate-sensitive infectious diseases also pose occupational risks to health workers, which may in turn undermine health protection for the wider population (World Health Organization, 2009b). Other mechanisms include elevated occupational exposures to toxic chemical solvents which evaporate faster at higher temperatures (Bennett and McMichael, 2010) and rising temperatures reducing sea ice and increasing risk of drowning in those engaged in traditional hunting and fishing in the Arctic (Ford *et al.*, 2008).

11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2009b). Temperature and humidity were both included, and the modeling took into account the changes in the workforce distribution relating to the need for physical activity. In Southeast Asia, in 2050, the model indicates that more than half the afternoon work hours will be lost due to the need for rest breaks (Kjellstrom *et al.*, 2013). By 2100, under RCP4.5, Dunne *et al*. (2013) project up to a 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom *et al.*, 2011; Kjellstrom *et al.*, 2009a; Sahu *et al.*, 2013).

11.6.3. Mental Health

Harsher weather conditions such as floods, droughts, and heat waves tend to increase the stress on all those who are already mentally ill, and may create sufficient stress for some who are not yet ill to become so (Berry *et al.*, 2010). Manifestations of disaster-related psychiatric trauma include severe anxiety reactions (such as post-traumatic stress) and longer-term impacts such as generalised anxiety, depression, aggression, and complex psychopathology (Ahern *et al.*, 2005; Ronan *et al.*, 2008). For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Alston and Kent, 2008; Hanigan *et al.*, 2012). Extreme weather conditions may have indirect effects on those with mental illness, through the impacts on agricultural productivity, fishing, forestry and other economic activities. Disasters such as cyclones, heat waves and major floods may also have destructive effects in cities. Here again, the mentally ill may be at risk: cities often feature zones of concentrated disadvantage where mental disorders are more common (Berry, 2007) and there is also higher risk of natural disasters (such as flooding).

In addition to effects of extreme weather events on mental health via the risk/disadvantage cycle, there may be a distressing sense of loss, known as 'solastalgia,' that people experience when their land is damaged (Albrecht *et al.*, 2007) and they lose amenity and opportunity.

11.6.4. Violence and Conflict

Soil degradation, freshwater scarcity, population pressures and other forces that are related to climate are all potential causes of conflict. The relationships are not straightforward, however, as many factors influence conflict and violence. The topic is reviewed closely in Chapter 12, which concludes that factors associated with risk of violent conflict, such as poverty and impaired state institutions, are sensitive to climate variability, but evidence of an effect of climate change on violence is contested. Also, it is noted that populations affected by violence are particularly vulnerable to the impacts of climate change on health and social well-being.

11.7. Adaptation to Protect Health

Climate change may threaten the progress that has been made in reducing the burden of climate-related disease and injury. The degree to which programs and measures will need modification to address additional pressures from climate change will depend on the current burden of ill-health, the effectiveness of current interventions, projections of where, when, and how the health burden could change with climate change, the feasibility of implementing additional programs, other stressors that could increase or decrease resilience, and the social, economic, and political context for intervention (Ebi *et al.*, 2006).

The scientific literature on adaptation to climate change has expanded since AR4, and there are many more national adaptation plans that include health, but investment in specific health protection activities is growing less rapidly. A review by the World Health Organization in 2012 estimated that commitments to health adaptation internationally amount to less than 1% of the annual health costs attributable to climate change in 2030 (World Health Organization Regional Office for Europe, 2013).

The value of adaptation is demonstrated by the health impacts of recent disasters associated with extreme weather and climate events, although not necessarily attributed with confidence to climate change itself. For example, approximately 500,000 people died when cyclone Bhola (category 3 in severity) hit East Pakistan (present day Bangladesh) in 1970. In 1991, a cyclone of similar severity caused about 140,000 deaths. In November 2007, cyclone Sidr (category 4) resulted in approximately 3,400 deaths; the population had grown by more than 30 million in the intervening period (Mallick *et al.*, 2005). Bangladesh achieved this remarkable reduction in mortality through effective collaborations between governmental and non-governmental organizations and local communities (Khan, 2008). Alongside improving general disaster education (greatly assisted by rising literacy rates, especially among women), the country deployed early warning systems and built a network of cyclone shelters. Early warning systems included high technology information systems and relatively simple measures such as training volunteers to distribute warning messages by bicycle.

Efforts to adapt to the health impacts of climate change can be categorized as incremental, transitional, and transformational actions (O'Brien *et al.*, 2012). Incremental adaptation includes improving public health and health care services for climate-related health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation means shifts in attitudes and perceptions, leading to initiatives such as vulnerability mapping and improved surveillance systems that specifically integrate environmental factors. Transformational adaptation (see Chapter 16), which requires fundamental changes in systems, has yet to be implemented in the health sector.

11.7.1. Improving Basic Public Health and Health Care Services

Although the short time period since health adaptation options have been implemented means evidence of effectiveness in specifically reducing climate change-related impacts is currently lacking, there is abundant evidence of steps that may be taken to improve relevant public health functions (Woodward *et al.*, 2011). This is important because the present health status of a population may be the single most important predictor of both the future health impacts of climate change and the costs of adaptation (Pandey, 2010). Most health adaptation focuses on improvements in public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring environmental exposures, improving disaster risk management, and facilitating coordination between health and other sectors to deal with shifts in the incidence and geographic range of diseases (Woodward *et al.*, 2011).

Examples of incremental health care interventions include introduction of vaccination programs in the United States, after which seasonal outbreaks of rotavirus, a common climate-sensitive pathogen, were delayed and diminished in magnitude (Tate *et al.*, 2009). Post-disaster initiatives also are important. For example, an assessment of actions to improve the resilience of vulnerable populations to heat waves recommended staff planning over the summer period, cooling of health care facilities, training of staff to recognize and treat heat strain, and monitoring of those in the highest risk population groups (World Health Organization Regional Office for Europe, 2009). Ensuring essential medical supplies for care of individuals with chronic conditions, including effective post-disaster distribution, would increase the ability of communities to manage large-scale floods and storms. In Benin, one measure proposed as part of the national response to sea level rise and flooding is expanded health insurance arrangements, so that diseases such as malaria and enteric infections can be treated promptly and effectively (Dossou and Glehouenou-Dossou, 2007).

11.7.2. Health Adaptation Policies and Measures

Transitional adaptation moves beyond focusing on reducing the current adaptation deficit to considerations of how a changing climate could alter health burdens and the effectiveness of interventions (Frumkin *et al.*, 2008). For example, maintaining and improving food safety in the face of rising temperatures and rainfall extremes depends on effective interactions between human health and veterinary authorities, integrated monitoring of food-borne and animal diseases, and improved methods to detect pathogens and contaminants in food (Tirado *et al.*, 2010). Indicators of community functioning and connectedness also are relevant because communities with high levels of social capital tend to be more successful in disseminating health and related messages, providing support to those in need (Frumkin *et al.*, 2008).

Vulnerability Mapping

Vulnerability mapping is being increasingly used to better understand current and possible future risks related to climate change. For example, Reid *et al*. (2009) mapped community determinants of heat vulnerability in the U.S.A. The four factors explaining most of the variance were a combination of social and environmental factors, social isolation, prevalence of air conditioning, and the proportion of the population who were elderly or diabetic. Remote sensing technologies are now sufficiently fine-grained to map local vulnerability. For example, these technologies can be used to map surface temperatures and urban heat island effects at the neighborhood scale, indicating where city greening and other urban cooling measures could be most effective, and alerting public health authorities to populations that may be at greatest risk of heat waves (Luber and McGeehin, 2008). In another example, spatial modeling of geo-referenced climate and environmental information was used to identify characteristics of domestic malaria transmission in 2009-2012 in Greece, to guide malaria control efforts (Sudre *et al.*, 2013). Mapping at regional and larger scales may be useful to guide adaptation actions. In Portugal, modeling of Lyme disease indicates that future conditions will be less favorable for disease transmission in the south, but more favorable in the center and northern parts of the country (Casimiro *et al.*, 2006). This information can be used to modify surveillance programs before disease outbreaks occur. To capture a more complete picture of vulnerability, mapping exercises also could consider climate sensitivity and adaptation capacity, such as was done in an assessment of climate change and risk of poverty in Africa (Thornton *et al.*, 2008).

11.7.3. Early Warning Systems

Early warning systems have been developed in many areas to prevent negative health impacts through alerting public health authorities and the general public about climate-related health risks. Effective early warning systems take into consideration the range of factors that can drive risk and are developed in collaboration with end users.

Components of effective early warning systems include forecasting weather conditions associated with increased morbidity or mortality, predicting possible health outcomes, identifying triggers of effective and timely response plans that target vulnerable populations, communicating risks and prevention responses, and evaluating and revising the system to increase effectiveness in a changing climate (Lowe *et al.*, 2011). Heat wave early warning systems are being increasingly implemented, primarily in high-income countries. Of eight studies of the effectiveness of heat wave early warning systems or heat prevention activities to reduce heat-related mortality, seven reported fewer deaths during heat waves after implementation of the system (Chau *et al.*, 2009; Ebi *et al.*, 2004; Fouillet *et al.*, 2008; Palecki *et al.*, 2001; Tan *et al.*, 2007; Weisskopf *et al.*, 2002) ; only Morabito *et al.* (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures with about 2,000 excess deaths. This was over 4,000 fewer deaths than was anticipated on the basis of what occurred in the 2003 heat wave. A national assessment attributed the lower than expected death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet *et al.*, 2008). A review of the heat wave early warning systems in the twelve European countries with such plans concluded that evaluations of the effectiveness of these systems is urgently needed to inform good practices, particularly understanding which actions increase resilience (Lowe *et al.*, 2011).

Early warning systems have been developed also for vector-borne and food-borne infections, although evidence of their effectiveness in reducing disease burdens is limited. In Botswana, an early warning system forecasts malaria incidence up to 4 months in advance based on observed rainfall; inter-annual and seasonal variations in climate are associated with outbreaks of malaria in this part of Africa. Model outputs include probability distributions of disease risk and measures of the uncertainty associated with the forecasts (Thomson *et al.*, 2006). A weather-based forecasting model for dengue, developed in Singapore, predicted epidemics 13 months ahead of the peak in new cases, which gave the national control program time to increase control measures (Hii *et al.*, 2012). A study of campylobacteriosis in the United States developed models of monthly disease risk with a very good fit in validation data sets (R^2 up to 80%) (Weisent *et al.*, 2010).

11.7.4. Role of Other Sectors in Health Adaptation

Other sectors, including ecosystems, water supply and sanitation, agriculture, infrastructure, energy and transportation, land use management, and others, play an important part in determining the risks of disease and injury resulting from climate change.

Within the context of the EuroHEAT project, a review of public health responses to extreme heat in Europe identified transport policies, building design, and urban land use as important elements of national and municipal heat wave and health action plans (World Health Organization Regional Office for Europe, 2009). A study examining well-established interventions to reduce the urban heat island effect (replacing bitumen and concrete with more heat-reflective surfaces, and introducing more green spaces to the city) estimated these would reduce heat-related emergency calls for medical assistance by almost 50% (Silva *et al.*, 2010). Urban green spaces lower ambient temperatures, improve air quality, provide shade, and may be good for mental health (van den Berg *et al.*, 2010). However, the extent to which changes in these factors reduce heat wave-related morbidity and mortality depend on location. A study in London, UK, found that built form and other dwelling characteristics more strongly influenced indoor temperatures during heat waves than did the urban health island effect (Oikonomou and Wilkinson, 2012).

A review of food aid programs indicates that a rapid response to the risk of child under-nutrition, targeted to those in greatest need, with flexible financing and the capacity to rapidly scale-up depending on need, may reduce damaging health consequences (Alderman, 2010). Community-based programs designed for other purposes can facilitate adaptation, including disaster risk management. In the Philippines, for example, interventions in low-income urban settings with the potential to reduce the harmful effects of climate extremes on health include savings schemes, small-scale loans, hygiene education, local control and maintenance of water supplies, and neighborhood level solid waste management strategies (Dodman *et al.*, 2010). It is important to note that climate change adaptation in other sectors may influence health in a positive manner (eg re-vegetation of watersheds to improve water quality), or on occasion, exacerbate health risks (eg urban wet-lands designed primarily for flood control may promote mosquito breeding) (Medlock and Vaux, 2011).

11.8. Adaptation Limits under High Levels of Warming

Most attempts to quantify health burdens associated with future climate change consider modest increases in global average temperature, typically less than 2° C. However, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above pre-industrial temperatures (Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012; Rogelj *et al.*, 2009). It is therefore increasingly important to examine the likely health consequences of warming beyond 2°, including extreme warming of 4-6°C or higher. Predictions of this nature are limited by uncertainty about climatic as well as key, non-climatic determinants of health including the nature and degree of adaptation. Here, we instead focus primarily on physiological or ecological limits that constrain our ability to adapt and protect human health and wellbeing (Section 16.4.1).

It can be assumed that the increase in many important climate-related health impacts at increasingly higher levels of warming will be greater than simple linear increments; that is, that the health consequences of a 4°C temperature increase will be more than twice those of a +2°C world (see Figure 11-6). Nonlinear and threshold effects have been observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, 2013a), agricultural crop yields, as key determinants of childhood nutrition and development (Lobell *et al.*, 2011a; Schlenker and Roberts, 2009), and infectious diseases (Altizer *et al.*, 2006) , for example. These are also briefly elaborated here.

[INSERT FIGURE 11-6 HERE
Figure 11-6: Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11.The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill-health globally at present and should not be considered completely independent. Impact levels are presented for the near-term era of committed climate change (2030-2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, e.g., vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term era of climate options (2080-2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.]

11.8.1. Physiological Limits to Human Heat Tolerance

In standard (or typical) conditions, core body temperatures will reach lethal levels under sustained periods of wet-bulb temperatures above about 35°C (Sherwood and Huber, 2010). Sherwood and Huber (2010) conclude that a global mean warming of roughly 7°C above current temperatures would create small land areas where metabolic heat dissipation would become impossible. An increase of 11-12°C would enlarge these zones to encompass most of the areas occupied by today's human population.

The above analysis is likely a conservative estimate of an absolute limit to human heat tolerance because working conditions are hazardous at lower thresholds. The U.S. military, for example, suspends all physical training and strenuous exercise when the wet bulb globe temperature (WBGT) exceeds 32°C (Willett and Sherwood, 2012) while international labor standards suggest the time acclimatized individuals spend doing low intensity labor such as office work be halved under such conditions (Kjellstrom *et al.*, 2009a).[1] One estimate suggests global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200 under the RCP 8.5 scenario in which global mean temperatures rise 3.4°C by 2100 and 6.2°C by 2200 relative to 1861-1960 (Dunne *et al.*, 2013). It is projected that tropical and mid-latitude regions including India, Northern Australia, Southeastern USA will be particularly badly affected (Dunne et al., 2013; Willett and Sherwood, 2012).

[FOOTNOTE 1: WBGT is a heat index closely related to the wet-bulb temperature that also incorporates measures of radiant heat from the Sun and evaporative cooling due to wind.]

11.8.2. Limits to Food Production and Human Nutrition

Agricultural crops and livestock similarly have physiological limitations in terms of thermal and water stress. For example, production of the staple crops maize, rice, wheat and soybean is generally assumed to face an absolute temperature limit in the range of 40-45°C (Teixeira *et al.*, 2011), while key phenological stages such as sowing to emergence, grain-filling, and seed set have maximum temperature thresholds near or below 35°C (Porter and Semenov, 2005; Porter and Gawith, 1999; Yoshida *et al.*, 1981). The existence of critical climatic thresholds and evidence of non-linear responses of staple crop yields to temperature and rainfall (Brázdil *et al.*, 2009; Lobell *et al.*, 2011b; Schlenker and Roberts, 2009) thus suggest that there may be a threshold of global warming beyond which current agricultural practices can no longer support large human civilizations, and the impacts on malnourishment and undernutrition described in Section 11.6.1 will become much more severe. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures generally incorporate neither critical thresholds nor nonlinear response functions (Lake *et al.*, 2012; Lloyd *et al.*, 2011), reflecting uncertainties about exposure-response relations, future extreme events, the scale and feasibility of adaptation, and climatic thresholds for other influences such as infestations and plant diseases. Extrapolation from current models nevertheless suggests that the global risk to food security becomes very severe under an increase of 4-6°C or higher in global mean temperature (*medium evidence, high agreement*) (Chapter 7, Executive Summary).

11.8.3. Thermal Tolerance of Disease Vectors

Substantial warming in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries, as already evidenced by the northward extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis (Lindgren and Gustafson, 2001; Ogden *et al.*, 2006). On the other hand, the emergence of new temperature regimes that exceed optimal conditions for vector and host species will reduce the potential for infectious disease transmission and, with high enough temperature rise, may eventually eliminate some infectious diseases that exist at present close to their upper tolerable temperature limits. For example, adults of two malaria-transmitting mosquito species are unable to survive temperatures much above 40°C in laboratory experiments (Lyons *et al.*, 2012), although in the external world they may seek out tolerable microclimates. Reproduction of the malaria parasite within the mosquito is impaired at lesser raised temperatures (Paaijmans *et al.*, 2009). Larval development of *Aedes albopictus*, an Asian mosquito vector of dengue and chikungunya, also does not occur at or above 40°C (Delatte *et al.*, 2009).

11.8.4. Displacement & Migration under Extreme Warming

Weather extremes and longer term environmental change including sea level rise lead to both more people displaced and increase in populations that are effectively trapped (Section 12.4.1.2). This trend is expected to be more pronounced under extreme levels of warming (Section 16.5). Gemenne (2011) argues that the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes. Health studies of refugees, migrants, and people in resettlement schemes suggest that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael *et al.*, 2012). The health risks associated with forced displacement include undernutrition; food- and water-borne illnesses; diseases related to overcrowding such as measles, meningitis and acute respiratory infections; sexually-transmitted diseases; increased maternal mortality; and mental health disorders (McMichael *et al.*, 2012).

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves by enclosing places for living and working, first for their most vulnerable members: the young, old, ill, and manual laborers. This strategy will mean increased vulnerability to infrastructure failure and unreliable energy and water supplies. Electrical power outages have been linked to both accidental and disease-related deaths in temperate climates (Anderson and Bell, 2012), and failures in power supplies are more likely to occur during extreme weather events (Section 19.6.2.1). Large-scale reliance on air-conditioning under a significantly hotter climate regime would therefore pose a serious health risk.

11.9. Co-Benefits

Essentially every human activity affects (and is affected by) climate and health status in some way, but not all are strongly linked to either and even fewer strongly to both. Here we focus on measures to mitigate the atmospheric concentration of warming climate altering pollutants (CAPs) that also hold the potential to significantly benefit human health. These so-called co-benefits include health gains from strategies that are directed primarily at climate change, and mitigation of climate change from well-chosen policies for health advancement (Apsimon *et al.*, 2009; Haines *et al.*, 2007; Shindell *et al.*, 2012; Smith and Balakrishnan, 2009; UNEP, 2011). The literature on health co-benefits associated with climate change mitigation strategies falls into several categories (Smith and Balakrishnan, 2009; Smith *et al.*, 2009). These include: Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants in association with changes in energy production, energy efficiency, or control of landfills; Increase access to reproductive health services; Decrease meat consumption (especially from ruminants) and substitution of low-carbon healthy alternatives; Increase active transport particularly in urban areas; Increase urban green-space. In addition, although not discussed here, there are potential health side effects of mitigation measures, such as geoengineering, biofuel expansion, and carbon taxes that are potentially deleterious for human health (Tilman *et al.*, 2009). See WGII Ch 19. In Table 11-3, we summarize what is known about the main categories of co-benefits, but because of space limitation, we only provide additional detail for two of them below.

[INSERT FIGURE 11-7
Figure 11-7: Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars from the combined value of carbon offsets (valued at 10$/t$CO_2$e) and averted DALYs [$7450/DALY, which is representative of valuing each DALY at the average world GDP (PPP) per capita in 2000]. The vertical bar shows the range of the cut offs for cost-effective and very cost-effective health interventions in India and China using the WHO CHOICE criteria (World Health Organization, 2003). This figure evaluates only a small subset of all co-benefits opportunities and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines *et al*. (Haines *et al.*, 2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).]

[INSERT TABLE 11-3 HERE
Table 11-3: Examples of recent (post AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim *et al.* (2012).]

11.9.1. Reduction of Co-Pollutants

Most of the publications related to CAPs and health-damaging pollutants refer to fuel combustion and fall into three major categories: 1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants, providing these gains are not outpaced by increases in energy demand, and the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; 2) increases of combustion efficiency (decreasing emission of incomplete combustion products) will have both climate and health benefits, even if there is no change in energy efficiency and/or fuel itself is renewable, because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009); and 3) Increased use of non-combustion sources, such as wind, solar, tidal, wave and geothermal energy, would reduce emissions of warming CAPs and health damaging air pollutants, providing benefits for climate and health (Jacobson *et al.*, 2013).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell *et al.*, 2008) and household sources (Po *et al.*, 2011). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for a substantial percent of primary outdoor fine particle pollution as well, perhaps a quarter in India, for example (Lim *et al.*, 2012). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for much fine particle outdoor air pollution and may contribute to long-range transport of hazardous air pollutants (Anenberg *et al.*, 2013). This indicates that reductions in emissions from household sources will yield co-benefits through the outdoor pollution pathway as well.

If interventions result in reductions in coal combustion, there are a range of other potential health benefits beyond reduction of particulate air pollution emissions, including reducing other types of health-damaging emissions and the human impacts from coal mining (Lockwood, 2012; Smith *et al.*, 2013).

Another category of air pollution co-benefits comes from controls on methane emissions that both reduce radiative forcing and potentially reduce human exposures to ambient ozone, for which methane is a precursor.

11.9.1.1. Outdoor Sources

Primary co-pollutants, such as particulate matter (PM) and carbon monoxide (CO) are those released at the point of combustion, while secondary co-pollutants, such as tropospheric ozone and sulfate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett *et al.*, 2009) and can be transported long distances.

The burden of disease from outdoor exposures in a country may often be greater in populations with low socioeconomic status, both because of living in areas with higher exposures and because these populations often have worse health and are subjected to multiple additional negative environmental and social exposures (Morello-Frosch *et al.*, 2011).

11.9.1.2. Household Sources

Globally, the largest exposures from the pollutants from poor fuel combustion occur in the poorest populations. This is because household use of biomass for cooking is distributed nearly inversely with income. Essentially, no poor family can afford gas or electricity for cooking and very few families who can afford to do so, do not. Thus, the approximate 41% of all world households using solid fuels for cooking are all among the poor in developing countries (Bonjour *et al.*, 2013). Although biomass makes up the bulk of this fuel and creates substantial health impacts from products of incomplete combustion when burned in simple stoves (Lim *et al.*, 2012), probably the greatest health and largest climate impacts per household result from use of coal, which can also be contaminated with sulfur and a range of toxic elements as well (Edwards *et al.*, 2004; Zhang and Smith, 2007). Successfully accelerating the reduction of impacts from these fuels, however, has not been found to be easily accomplished with biomass/coal stove programs implemented to date and may require moving to clean fuels (Bruce *et al.*, 2013). The climate benefits from improving household biomass fuel combustion come in part from potential reduction of net warming by reducing emissions of aerosols (including black carbon), but more confidently from reduction of CH_4 and other CAPs that are produced by incomplete combustion, as well as reductions in net CO_2 emissions if interventions are applied in areas relying on non-renewably harvested wood fuel (WG1, Section 8.5.3).

11.9.1.3. Primary Co-Pollutants

Outdoor exposure to PM, especially to particles with diameters less than 2.5 µm ($PM_{2.5}$), contributes significantly to ill-health including cardio- and cerebrovascular disease, adult chronic and child acute respiratory illnesses, lung cancer, and possibly other diseases. The Comparative Risk Assessment (CRA) for outdoor air pollution done as part of the Global Burden of Disease (GBD) 2010 Project found approximately 3.2 million premature deaths globally from ambient particle pollution or about 3% of the global burden of disease (Lim *et al.*, 2012). Importantly, reductions in ambient PM concentrations have also been shown to decrease morbidity and premature mortality (Boldo *et al.*, 2010). A significant portion of ambient particle pollution derives from fuel combustion, perhaps 80% globally (GEA, 2012).

Because of higher exposures, an additional set of diseases has also been associated with combustion products in households burning biomass and/or coal for cooking and heating. Thus, in addition to the diseases noted above, cataracts, low birth weight, and stillbirth have been associated strongly with exposures to incomplete combustion products, such as PM and CO. CO has impacts on unborn children in utero through exposures to their pregnant mothers (World Health Organization Regional Office for Europe, 2010). There is also growing evidence of exacerbation of tuberculosis (Pokhrel *et al.*, 2010) in adults and cognitive effects in children (Dix-Cooper *et al.*, 2012). The CRA of the GBD-2010 found 3.5 million premature deaths annually from household air pollution derived from cooking fuels or 4.4% of the global burden of disease (Lim *et al.*, 2012). Importantly, there are also studies showing health benefits of household interventions, for child pneumonia (Smith *et al.*, 2011) blood pressure (Baumgartner *et al.*, 2011; McCracken *et al.*, 2007) , lung cancer (Lan *et al.*, 2002) , and chronic obstructive pulmonary disease (Chapman *et al.*, 2005). Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million in 2010 or 4.9% of the global burden of disease (Lim *et al.*, 2012).

Black carbon (BC), a primary product of incomplete combustion, is both a strong CAP and health-damaging (Bond *et al.*, 2013; IPCC, 2007; Ramanathan and Carmichael, 2008). A systematic review, meta-analysis, and the largest cohort study to date of the health effects of BC found that there were probably stronger effects on mortality from exposure to BC than for undifferentiated fine particles ($PM_{2.5}$) (Smith *et al.*, 2009). Reviews have concludes that abatement of particle emissions including BC represents an opportunity to achieve both climate mitigation and health benefits (Shindell *et al.*, 2012; UNEP, 2011). WG1 (Box TS-6), however, concluded that the net impact of BC emissions reductions overall is not certain as to sign, i.e., whether net warming or cooling. Nevertheless, there would be climate (and health) benefits in circumstances where BC is emitted without many other cooling aerosols, as with diesel and kerosene combustion (Lam *et al.*, 2012).

Other examples of climate forcing, health-damaging co-pollutants of CO_2 from fuel use are carbon monoxide, non-methane hydrocarbons, and sulfur and nitrogen oxides. Each co-pollutant poses risks as well as being climate altering in different ways. See WGI for more on climate potential and WHO reviews of health impacts (World Health Organization Regional Office for Europe, 2010; World Health Organization, 2006).

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong GHG, methane (CH_4) is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is both a GHG and damaging to health, crops, and ecosystems (WG1 TS.5.4.8). Thus, reductions in CH_4 could lead to reductions in ambient tropospheric ozone concentrations, which in turn could result in reductions in population morbidity and premature mortality and climate forcing.

One study found that a reduction of global anthropogenic CH_4 emissions by 20% beginning in 2010 could decrease the average daily maximum 8-h surface ozone by 1 ppb by volume, globally; sufficient to prevent 30,000 premature all-cause mortalities globally in 2030, and 370,000 between 2010 and 2030 (West, Fiore et al. 2012). CH_4 emissions are generally accepted as the primary anthropogenic source of tropospheric ozone concentrations above other human-caused emissions of ozone precursors (West *et al.*, 2007) and thus, the indirect health co-benefits of CH_4 reductions are epidemiologically significant. On the other hand, work done for the GBD-2010 estimated 150,000 premature deaths from all ozone exposures globally in 2010, indicating a more conservative interpretation of the evidence for mortality from ozone (Lim *et al.*, 2012).

In an analysis of ozone trends from 1998-2008 in the United States, Lefohn et al. (2010) found that 1-hour and 8-hour ambient ozone averages have either decreased or failed to increase due to successful regulations of ozone precursors, predominantly NO_x and CH_4. This is consistent with the US EPA (2010) conclusion that in the US, for the period 1980-2008, emissions of nitrogen oxides and volatile organic compounds fell by 40% and 47%, respectively (Lefohn *et al.*, 2010; US EPA, 2010). These results point to the effectiveness of reducing ambient ozone concentrations through regulatory tools that reduce the emissions of ozone precursors, some of which, like CH_4, are GHGs.

Not every CAP emitted from fuel combustion is warming. The most prominent example is sulfur dioxide emitted from fossil fuel combustion, which changes to particle sulfate in the atmosphere. Although health damaging, sulfate particles have a cooling effect on global radiative forcing. Thus, reduction of sulfur emissions, which is important for health protection, does not qualify as a co-benefit activity since it actually acts to unmask more of the warming effect of other CAP emissions (Smith *et al.*, 2009).

11.9.1.5. Case Studies of Co-Benefits of Air Pollution Reductions

A recent UNEP- and WMO-led study of black carbon and tropospheric ozone found that, if all of 400 proposed BC and CH_4 mitigation measures were implemented on a global scale, the estimated benefits to health would come predominately from reducing $PM_{2.5}$ (0.7 – 4.6 million avoided premature deaths; 5.3 – 37.4 million avoided years of life lost) compared to tropospheric ozone (0.04 – 0.52 million avoided premature deaths; 0.35 – 4.7 million avoided years of life lost) based on 2030 population figures (UNEP, 2011). About 98% of the avoided deaths would come from reducing $PM_{2.5}$, with 80% of the estimated health benefits occurring in Asia (Anenberg *et al.*, 2012). Another study of the reduction of PM and ozone exposures due to CAPs emissions controls and including climate change feedback showed potential reductions of 1.3 million premature deaths by 2050 with avoided costs of premature mortality many times those of the estimated cost of abatement (West *et al.*, 2013).

A study of the benefits of a hypothetical 10-year program to introduce advanced combustion cookstoves in India found that in addition to reducing premature mortality by about 2 million and DALYs by 55 million over that period, there would be reduction of 0.5-1.0 billion tons CO_2-eq (Wilkinson *et al.*, 2009). Another study of India found a potential to reduce 570 thousand premature deaths a year, one-third of national BC emissions, and 4% of all national greenhouse emissions by hypothetical substitution of clean household fuel technologies (Venkataraman *et al.*, 2010).

In their estimation of effects of hypothetical physical and behavioral modifications in UK housing, Wilkinson and colleagues (Wilkinson *et al.*, 2009) found that the magnitude and direction of implications for health depended heavily on the details of the intervention. However, the interventions were found to be generally positive for health. In a strategy of housing modification that included insulation, ventilation control, and fuel switching, along with behavioral changes, it was estimated that 850 fewer DALYs, and a savings of 0.6 megatonnes of CO_2 per million population in one year could be achieved. These calculations were made by comparing the health of the 2010 population with and without the specified physical and behavioral modifications (Wilkinson *et al.*, 2009).

Markandya *et al.* (2009) assessed the changes in emissions of $PM_{2.5}$ and subsequent effects on population health that could result from climate change mitigation measures aimed to reduce GHG emissions by 50% by 2050 (compared with 1990 emissions) from the electricity generation sector in the EU, China, and India In all three regions, changes in modes of production of electricity to reduce CO_2 emissions were found to reduce $PM_{2.5}$ and associated mortality. The greatest effect was found in India and the smallest in the EU. The analysis also found that if the health benefits were valued similarly to the approach used by the EU for air pollution, they offset the cost of GHG emission reductions, especially in the Indian context where emissions are high but costs of implementing the measures are low (Markandya *et al.*, 2009).

11.9.2. Access to Reproductive Health Services

Population growth influences the consumption of resources and emissions of CAPs (Cohen, 2010). Although population growth rates and total population size do not alone determine emissions, population size is an important factor. One study showed that CO_2 emissions could be lower by 30% by 2100 if access to contraception was provided to those women expressing a need for it (O'Neill *et al.*, 2010). Providing the unmet need for these services in areas such as the Sahel region of Africa that has both high fertility and high vulnerability to climate change can potentially significantly reduce human suffering as climate change proceeds (Potts and Henderson, 2012). This is important not only in poor countries, however, but also some rich ones like the US, where there is unmet need for reproductive health services as well as high CO_2 emissions per capita (Cohen, 2010). Also, because of income rise in developing countries and concurrent reduction of greenhouse emissions in developed countries, a convergence in emissions per capita is expected in most scenarios by 2100 (WG1 TS5.2). Slowing population growth through lowering fertility, as might be achieved by increasing access to family planning, has been associated with improved maternal and child health – the co-benefit - in two main ways: increased birth spacing and reducing births by very young and old mothers.

11.9.2.1. Birth and Pregnancy Intervals

Current evidence supports, with medium confidence, that short birth intervals (defined as birth intervals ≤24 months and inter-pregnancy intervals <6 months) are associated with increased risks of uterine rupture and bleeding (placental abruption and placenta previa) (Bujold *et al.*, 2002; Conde-Agudelo *et al.*, 2007).

There is also a correlation between short birth interval and elevated risk of low-birth-weight (Zhu, 2005). Zhu (2005) found, in a review of three studies performed in the United States that the smallest risk of low birth weight was found with inter-pregnancy spacing between 18-23 months. Another review of five cohort studies found that a birth interval shorter than 18 months was significantly associated with decreased low birth weight, preterm birth, and infant mortality after controlling for confounding factors (Kozuki *et al.*, 2013).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing and reductions in child, infant and neonatal mortality (Figure 11-S3) with risk of child undernutrition and mortality both increasing with shorter birth intervals (Rutstein, 2005). One study estimated that shifting birth spacing from current patterns in the world to a minimum of 24 months would reduce by 20% (~2 million) the current excess child mortality in the world (Gribble *et al.*, 2009; Rutstein, 2005).

11.9.2.2. Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, and these are also the age groups that most often want to control their fertility (Engelman, 2010). Women who begin child bearing under the age of 20 years are at an increased risk of developing pregnancy complications such as cephalopelvic disproportion, obstructed labor, preterm delivery, toxemia, bleeding, and maternal death (Tsui *et al.*, 2007). Additionally, children born to women under the age of 20 are at increased risk of fetal growth retardation and low birth weight, both of which can lead to long term physical and mental developmental problems (Tsui *et al.*, 2007). Childbearing at later ages (>35 years) is associated with increased risk of miscarriage and other adverse health outcomes (Cleary-Goldman *et al.*, 2005; Ujah *et al.*, 2005).

Providing access to family planning saves women's lives by reducing the total number of births and, in particular, through the reduction of births in high-risk groups (Prata, 2009) while simultaneously reducing total fertility and subsequent CAP emissions. Studies have found that when women have access to family planning, it is the highest risk age groups (youngest and oldest women) who reduce their fertility the most. In other words, family planning has a differential impact on maternal mortality reduction through reducing births in the highest risk groups (Diamond-Smith and Potts, 2011).

11.10. Key Uncertainties and Knowledge Gaps

There is evidence that poverty alleviation, public health interventions such as provision of water and sanitation, and early warning and response systems for disasters and epidemics will help to protect health from climate risks. The key uncertainty is the extent to which society will strengthen these services, including taking into account the risks posed by climate change. With a strong response, climate change health effects are expected to be relatively small in the next few decades, but otherwise climate-attributable cases of disease and injury will steadily increase.

Since AR4, national governments, through the World Health Assembly, have specifically called for increased research on (i) the scale and nature of health risks from climate change; (ii) effectiveness of interventions to protect health; (iii) health implications of adaptation and mitigation decisions taken in other sectors, (iv) improvement in decision support systems and surveillance, and (v) estimation of resource requirements. A recent scoping review identified quantitative peer-reviewed studies across all of these areas, with the exception of studies on the effectiveness or cost-effectiveness of targeted adaptation measures (Hosking and Campbell-Lendrum, 2012). There are also comparatively few studies of vulnerability in low and middle income populations, or of more complex disease pathways, such as the effect of more extreme weather on water and sanitation provision and diarrhea rates, on zoonotic diseases, or mental health. Studies of health co-benefits of climate change mitigation policies also remain rare compared to the size of the potential health gains. Potential negative side effects also need to be addressed, for example those arising from biofuel policies that compete with food production.

Relevant research for health protection in the near term is therefore likely to come from cross-disciplinary studies, including public health decision makers, in the following areas; improved vulnerability and adaptation assessments that focus on particularly vulnerable populations and encompass complex causal pathways; quantitative estimation of the effectiveness of health adaptation measures; surveillance, monitoring, and observational systems that link climate, health and economic impact data and provide a basis for early warning systems as well as development of future scenarios; assessment of the health co-benefits of alternative climate mitigation policies.

In the longer term, research will need to make the best use of traditional epidemiologic methods, while also taking into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and effects on multiple physical and biotic systems, with the potential for diverse and widespread effects, including high-impact events. There are low-probability, but plausible, scenarios for extreme climate regimes before the end of the century. Although difficult, it is important to develop robust methods to investigate the health implications of conditions that may apply in 2100, as decisions today about mitigation will determine their likelihood. Given the increase globally in life expectancies, many babies born this decade will be alive at the end of the century, and will be personally affected by the climate that is in place in 2100.

Frequently Asked Questions

FAQ 11.1: How does climate change affect human health? *[to remain at the end of the chapter]*
Climate change affects health in three ways; 1) Directly, such as the mortality and morbidity (including "heat exhaustion") due to extreme heat events, floods, and other extreme weather events in which climate change may play a role; 2) Indirect impacts from environmental and ecosystem changes, such as shifts in patterns of disease-carrying mosquitoes and ticks, or increases in waterborne diseases due to warmer conditions and increased precipitation and runoff; and 3) indirect impacts mediated through societal systems, such as undernutrition and

mental illness from altered agricultural production and food insecurity, stress and undernutrition and violent conflict caused by population displacement, economic losses due to widespread "heat exhaustion" impacts on the workforce, or other environmental stressors, and damage to health care systems by extreme weather events.

FAQ 11.2: Will climate change have benefits for health? *[to remain at the end of the chapter]*
Yes. For example some populations in temperate areas may be at less risk from extreme cold, and may benefit from greater agricultural productivity, at least for moderate degrees of climate change. Some areas currently prone to flooding may become less so. However, the overall impact for nearly all populations and for the world as a whole is expected to be more negative than positive, increasingly so as climate change progresses. In addition, the latitude range in the world that may benefit from less cold (e.g. the far north of the Northern Hemisphere) has fewer inhabitants compared with the equatorial latitudes where the burden will be greatest.

FAQ 11.3: Who is most affected by climate change? *[to remain at the end of the chapter]*
While the direct health effects of extreme weather events receive great attention, climate change mainly harms human health by exacerbating existing disease burdens and negative impacts on daily life among those with the weakest health protection systems, and with least capacity to adapt. Thus, most assessments indicate that poor and disenfranchised groups will bear the most risk and, globally, the greatest burden will fall on poor countries, particularly on poor children, who are most affected today by such climate-related diseases as malaria, undernutrition, and diarrhea. However, the diverse and global effects of climate change mean that higher income populations may also be affected by extreme events, emerging risks, and the spread of impacts from more vulnerable populations.

FAQ 11.4: What is the most important adaptation strategy to reduce the health impacts of climate change?
[to remain at the end of the chapter]
In the immediate future, accelerating public health and medical interventions to reduce the present burden of disease, particularly diseases in poor countries related to climatic conditions, is the single most important step that can be taken to reduce the health impacts of climate change. Priority interventions include improved management of the environmental determinants of health (such as provision of water and sanitation), infectious disease surveillance, and strengthening the resilience of health systems to extreme weather events. Alleviation of poverty is also a necessary condition for successful adaptation.

There are limits to health adaptation, however. For example, the higher-end projections of warming indicate that before the end of the 21st Century, parts of the world would experience temperatures that exceed physiological limits during periods of the year, making it impossible to work or carry out other physical activity outside.

FAQ 11.5: What are health "co-benefits" of climate change mitigation measures?
[to remain at the end of the chapter]
Many mitigation measures that reduce emissions of climate-altering pollutants (CAPs) have important direct health benefits in addition to reducing the risk of climate change. This relationship is called "co-benefits." For example, increasing combustion efficiency in households cooking with biomass or coal could have climate benefits by reducing CAPs and at the same time bring major health benefits among poor populations. Energy efficiency and reducing reliance on coal for electricity generation not only reduces emissions of greenhouse gases, but also reduces emissions of fine particles which cause many premature deaths worldwide as well as reducing other health impacts from the coal fuel cycle. Programs that encourage "active transport" (walking and cycling) in place of travel by motor vehicle reduce both CAP emissions and offer direct health benefits. A major share of greenhouse gas emissions from the food and agriculture sector arises from cows, goats and sheep – ruminants that create the greenhouse gas methane as part of their digestive process. Reducing consumption of meat and dairy products from these animals may reduce ischemic heart disease (assuming replacement with plant-based polyunsaturates) and some types of cancer. Programs to provide access to reproductive health services for all women will not only lead to slower population growth and its associated energy demands, but also will reduce the numbers of child and maternal deaths.

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Table 11-1: The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).

Disease	Area	Cases-yr	Climate Sensitivity and Confidence in Climate Effect	Key references
Mosquito-borne diseases				
Malaria	Mainly Africa, SE Asia	about 220 million	Temperature > +- 1; Precipitation > +- 1; Precipitation < -; Humidity > +-	WHO 2008, Kelly-Hope et al 2009, Omumbo et al 2011, Alonso et al 2011
Dengue	100 countries esp Asia Pacific	about 50 million	Temperature > +; Precipitation > +; Temperature < -; Precipitation < -; Humidity > +-	Beebe 2009, Descloux 2012, Earnest et al 2012, Pham et al 2011, Astrom et al 2012
Tick-borne diseases				
Tick-borne encephalitis	Europe, Russian Fed Mongolia, China	about 10,000	Temperature > +	Tokarevich et al 2011
Lyme	Temperate areas of Europe, Asia, North America	about 20,000 in USA	Temperature > +; Humidity > +	Bennet 2006, Ogden et al 2008
Other vector-borne diseases				
Hemorrhagic fever with renal syndrome (HFRS)	Global	0.15 – 0.2 million	Temperature > +; Precipitation > +; Humidity > +	Fang et al 2010
Plague	Endemic in many locations worldwide	about 40,000	Temperature > +; Precipitation > +	Stenseth et al 2006, Xu et al 2011, Ari et al 2010

Climate drivers: Temperature, Precipitation, Humidity

Climate driver variables: Increase or decrease: > Increased, < Decreased; # of cases: + More, - Fewer; Footnote: 1 Effects are specific to Anopheles spp

Confidence levels: High confidence in global effect; High confidence in local effect; Low confidence in effect

Table 11-2: Number of under-nourished children less than 5 years of age (in millions) in 2000 and 2050, using the NCAR (National Center for Atmospheric Research) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers' productivity, and no CO_2 fertilization benefits. Adapted from Nelson *et al.* (2009).

Scenario	South Asia	East Asia/ Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East/ North Africa	Sub-Saharan Africa	All Developing Countries
2000	75.6	23.8	4.1	7.7	3.5	32.7	147.9
2050							
No climate change	52.3	10.1	2.7	5.0	1.1	41.7	113.3
Climate change	59.1	14.5	3.7	6.4	2.1	52.2	138.5

Table 11-3: Examples of recent (post AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim *et al.* (2012).

Co-benefit category	**Benefits for health**	**Benefits for climate**	**References in chronological order**
Reduction of co-pollutants from household solid fuel combustion [see also WGIII-7, WGIII-8, WGIII-9, WGIII-10]	Potentially reduce exposures that are associated with disease, chronic and acute respiratory illnesses, lung cancer, low birth weight and stillbirths, and possibly tuberculosis	Reduces CAP emissions associated with household solid fuel use including CO2, CO, black carbon, and CH4	Bell *et al.*, 2008 Smith *et al.*, 2008 Wilkinson *et al.*, 2009 Lefohn *et al.*, 2010 Venkataraman *et al.*, 2010 World Health Organization Regional Office for Europe, 2010 Po *et al.*, 2011 Anenberg *et al.*, 2012
Reduction of GHGs and associated co-pollutants from industrial sources, such as power plants and landfills by more efficient generation or substitution of low carbon alternatives [27.3.7.2]	Reductions health-damaging co-pollutant emissions would decrease exposures to outdoor air pollution and could reduce risks of cardiovascular disease, chronic and acute respiratory illnesses, lung cancer, and preterm birth.	Reductions in emissions of CO2, black carbon, CO, CH4,and other CAPs	Bell *et al.*, 2008 Apsimon *et al.*, 2009 Jacobson, 2009 Puppim de Oliveira *et al.*, 2009 Smith *et al.*, 2009 Tollefsen *et al.*, 2009 Dennekamp *et al.*, 2010 Jacobson, 2010 Nemet, *et al.*, 2010 Rive and Aunan, 2010 Shonkoff *et al.*, 2011 Shindell *et al.*, 2012 West *et al.*, 2012 West *et al.*, 2013
Energy efficiency. Actual energy reduction may sometimes be less than anticipated because part of the efficiency benefit is taken as more service	Reductions in fuel demand potentially can reduce emissions of CAPs associated with fuel combustion and subsequent exposures to pollutants that are known to be health damaging.	Reductions in emission of CAPs due to decreases in fuel consumption	Markandya *et al.*, 2009 Wilkinson *et al.*, 2009

Increases in active travel and reductions in pollution due to modifications to the built environment, including better access to public transport and higher density of urban settlements [See also 24.4, 24.5, 24.6, 24.7, 26.8,]	Increased physical activity; reduced obesity; reduced non communicable disease burden, health service costs averted; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety.	Reductions of CAP emissions associated with vehicle transport; Replacing existing vehicles with lower emission vehicles could reduce air pollution	Babey *et al.*, 2007 Reed and Ainsworth, 2007 Kaczynski and Henderson, 2008 Casagrande *et al.*, 2009 Jarrett *et al.*, 2009 Rundle *et al.*, 2009 Woodcock *et al.*, 2009 Durand *et al.*, 2011 Grabow *et al.*, 2011 McCormack and Shiell, 2011 Jensen *et al.*, 2013 Woodcock *et al.*, 2013
Healthy low GHG emission diets which can have beneficial effects on a range of health outcomes [See also Table 11.3]	Reduced dietary saturated fat in some populations (particularly from ruminants) and replacement by plant sources associated with decreased risk of (ischemic) heart disease, stroke, colorectal cancer (processed meat consumption) Increased fruit and vegetable consumption can reduce risk of chronic diseases. Reduced CH_4 emissions due to a decreased demand for ruminant meat products would reduce the tropospheric ozone.	Reductions in CO2 and CH4 emissions from energy-intensive livestock systems	McMichael *et al.*, 2007 Friel *et al.*, 2009 Sinha *et al.*, 2009 Smith and Balakrishnan, 2009 Jakszyn *et al.*, 2011 Hooper *et al.*, 2012 Pan *et al.*, 2012 Xu *et al.*, 2012
Greater access to reproductive health services	Lower child and maternal mortality from increased birth intervals and shifts in maternal age.	Potentially slower growth of energy consumption and related CAP emissions; less impact on land use change, etc.	Tsui *et al.* 2007 Gribble *et al.*, 2009 Prata, 2009 O'Neill *et al.*, 2010 Diamond-Smith and Potts, 2011 Potts and Henderson, 2012 Kozuki *et. al.*, 2013
Increases in urban green space [Table 25-5]	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status.	Reduces atmospheric CO2 via carbon sequestration in plant tissue and soil	Mitchell and Popham, 2007 Babey *et al.*, 2008 Maas *et al.*, 2009 van den Berg *et al.*, 2010 van Dillen *et al.*, 2011
Carbon sequestration forest plantations, REDD and carbon offset sales [see Chpt 13, 15.3.4, see also 20.4.1, 26.8.4.3]	Poverty alleviation and livelihood/job generation through sale of CDM and voluntary market credits. Ameliorate declines in production or competitiveness in rural communities.	Reduces emissions of CAPs and promotes carbon sequestration through REDD	Holmes, 2010 Ezzine-de-Blas *et al.*, 2011

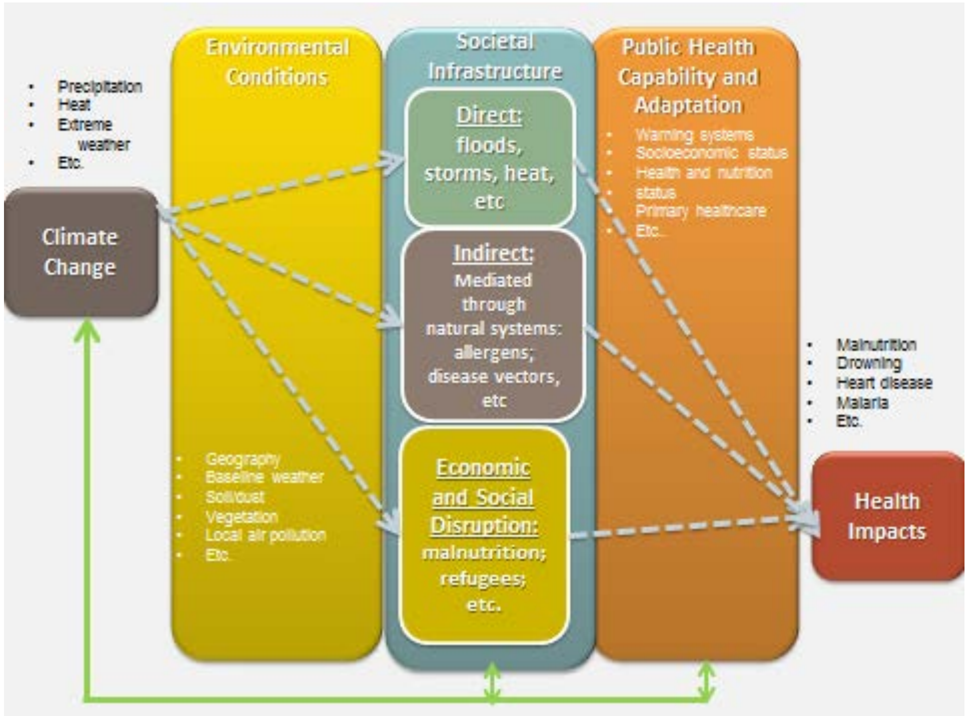

Figure 11-1: Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The yellow box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The orange box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health. Credit: E. Garcia, UC Berkeley.
[Illustration to be redrawn to conform to IPCC publication specifications.]

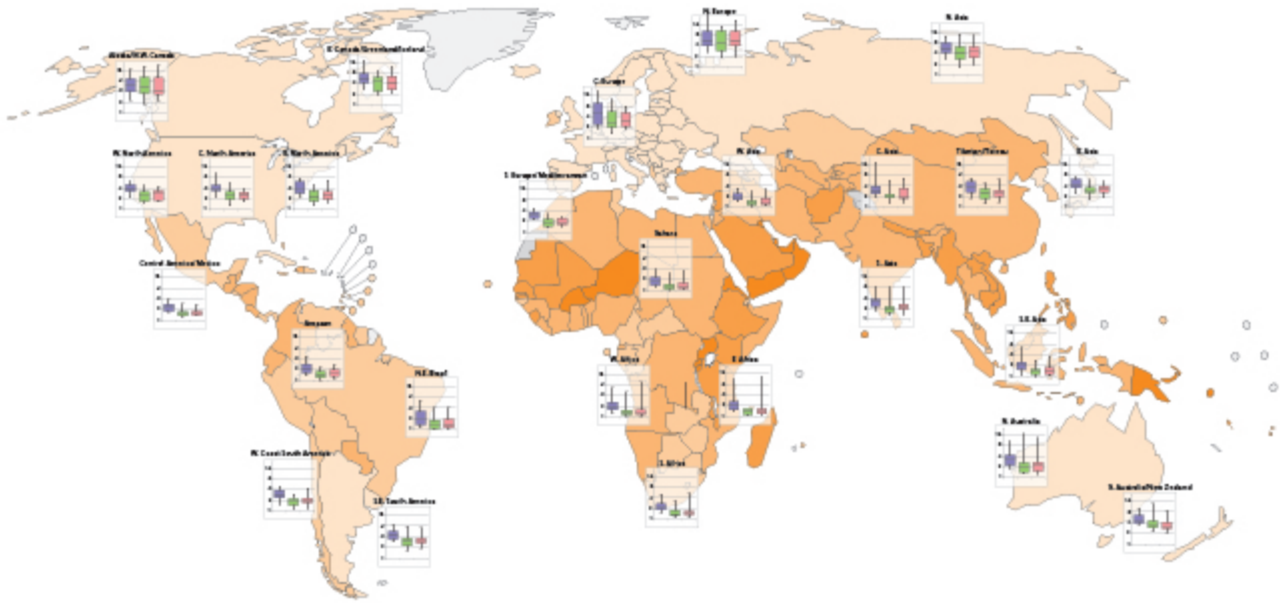

Figure 11-2: Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities – who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for 3 different "SRES" scenarios (Blue = B1; Green = A1B, Red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Coloured boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models. Source: World Health Organization and World Meteorological Organization, 2012.
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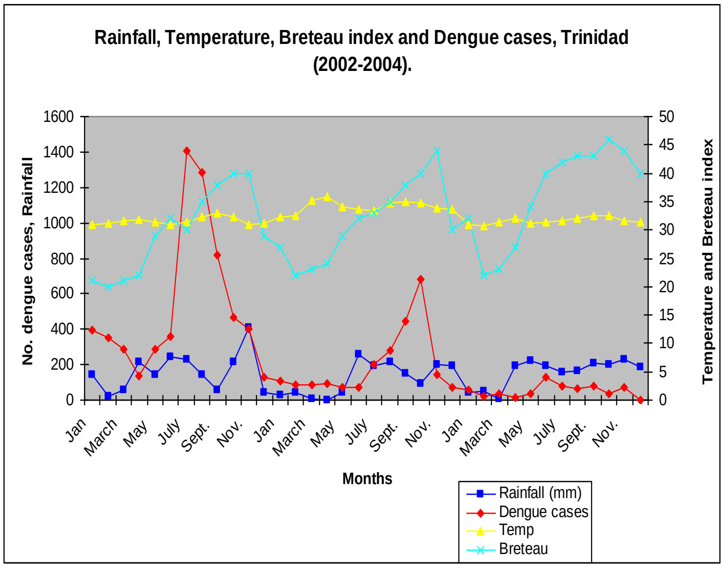


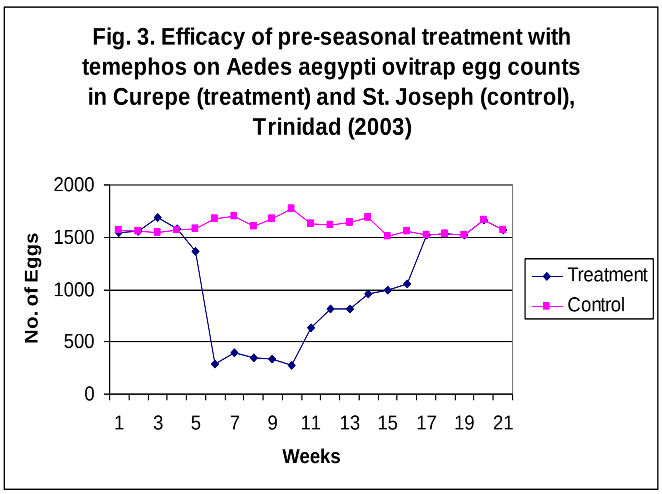


Figure 11-3: a) Rainfall, temperature, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002-2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined "dengue season" between June and November over two years of the study. Source: (Chadee *et al.*, 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission. Source: Chadee, 2009.
[Illustration to be redrawn to conform to IPCC publication specifications.]

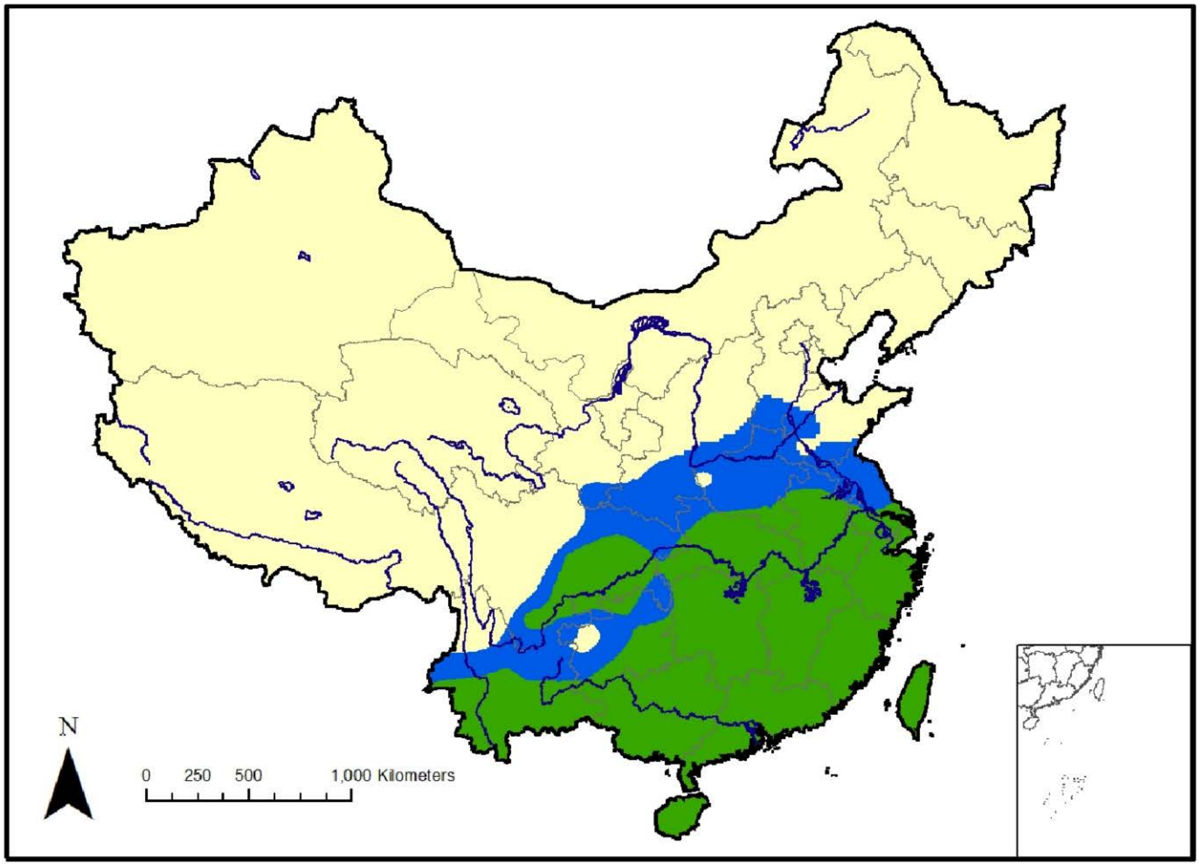
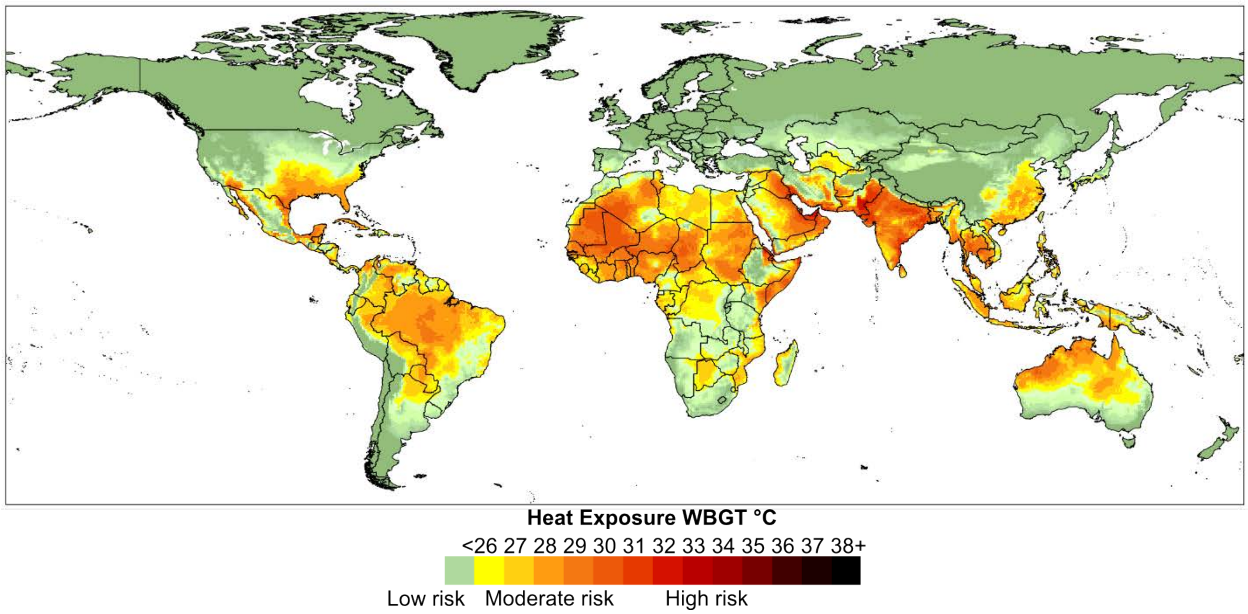
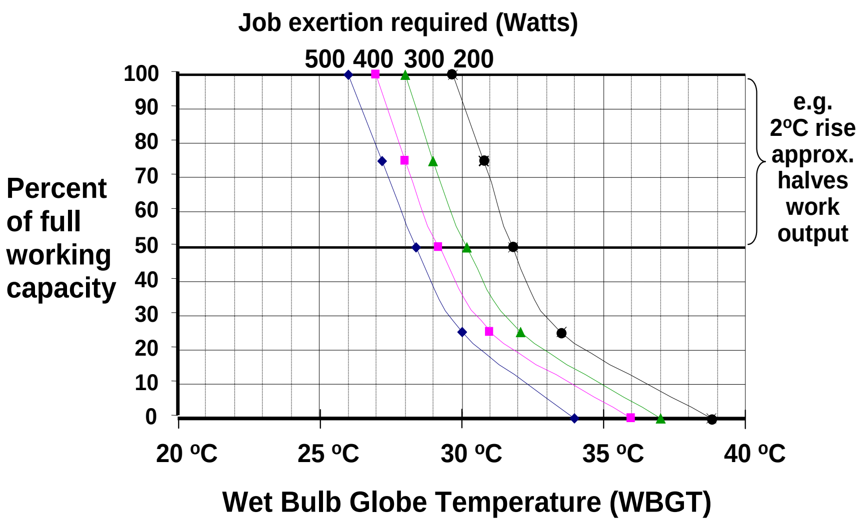


Figure 11-4: Effect of rising temperatures on the area in which transmission of *Schistosomiasis japonica* may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000. Adapted from Zhou *et al.*, 2008.
[Illustration to be redrawn to conform to IPCC publication specifications.]





This figure to be inserted in the Pacific Ocean area of the map above

Figure 11-5: The 1980-2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Standard Organization standard (1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that Tmax goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health. Source: Lemke and Kjellstrom, 2012.
[Illustration to be redrawn to conform to IPCC publication specifications.]

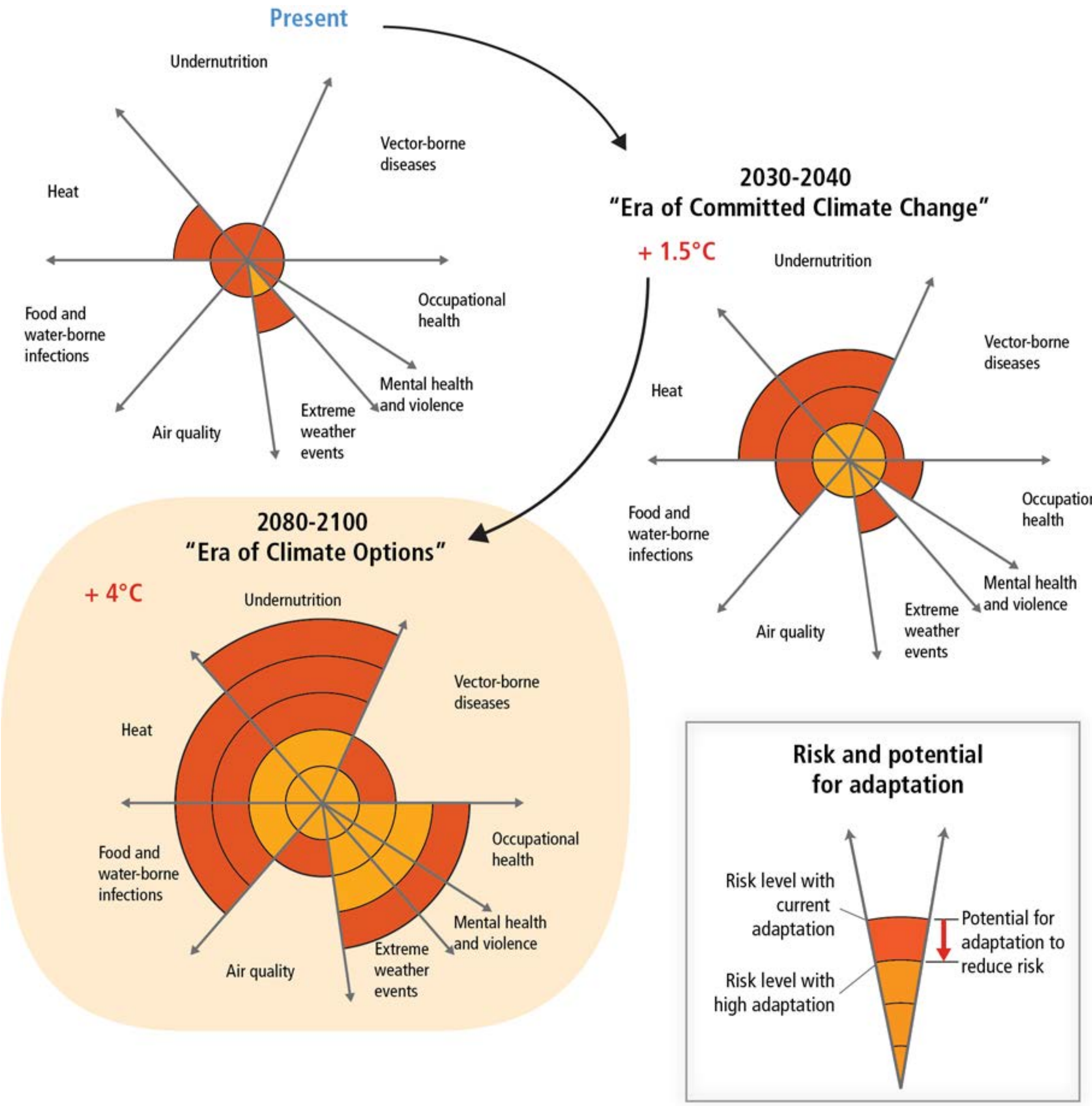


Figure 11-6: Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11.The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill-health globally at present and should not be considered completely independent. Impact levels are presented for the near-term era of committed climate change (2030-2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, e.g., vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term era of climate options (2080-2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.

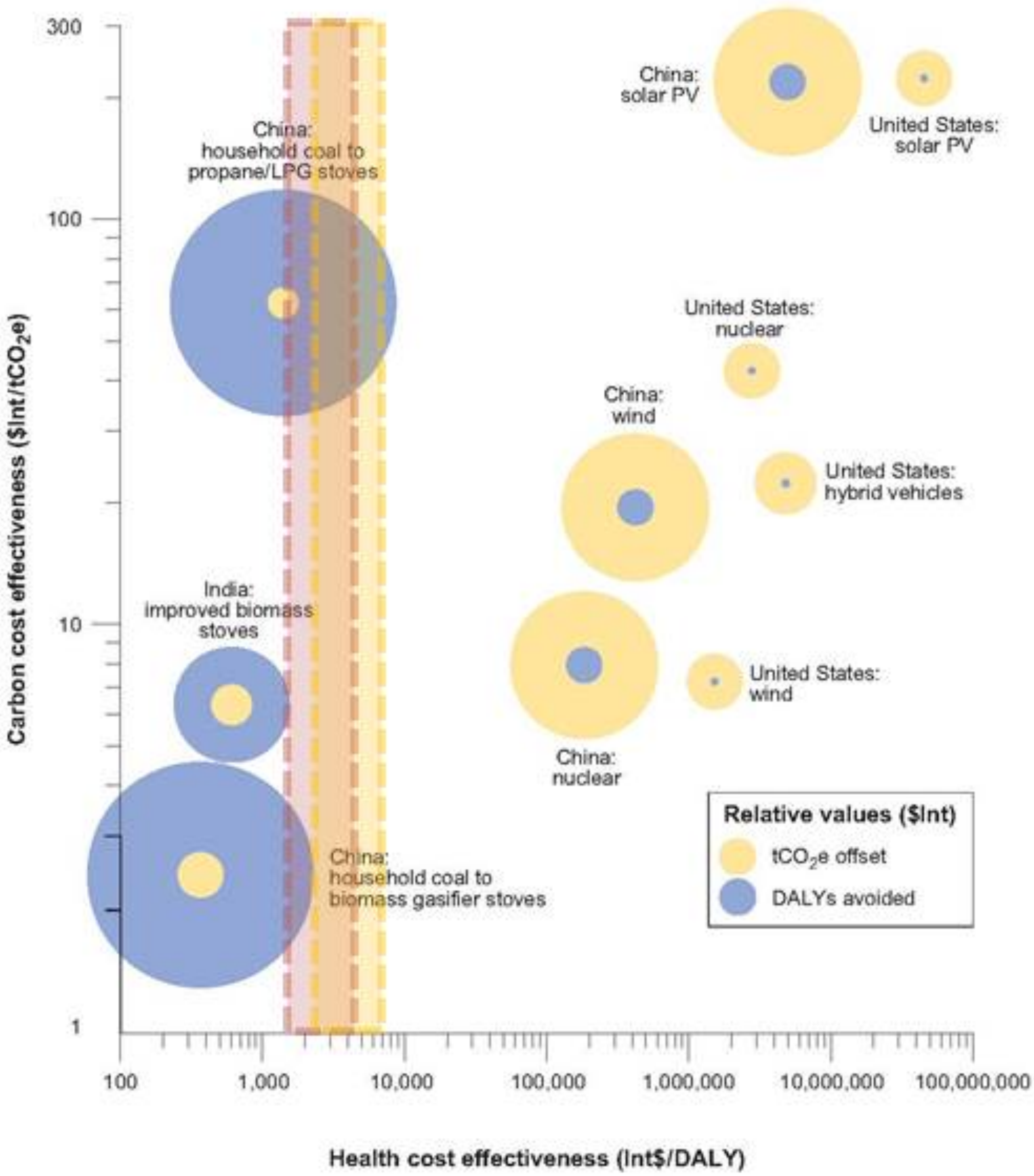


Figure 11-7: Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars from the combined value of carbon offsets (valued at 10$/t$CO_2$e) and averted DALYs [$7450/DALY, which is representative of valuing each DALY at the average world GDP (PPP) per capita in 2000]. The vertical bar shows the range of the cut offs for cost-effective and very cost-effective health interventions in India and China using the WHO CHOICE criteria (World Health Organization, 2003). This figure evaluates only a small subset of all co-benefits opportunities and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines *et al*. (Haines *et al.*, 2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).
[Illustration to be redrawn to conform to IPCC publication specifications.]