Chapter 11. Human Health

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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 changing incidence in temperature and humidity extremes and occurrence of floods, storms, 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 is a risk factor in its own right – it is more difficult to protect human health in a highly variable climate than one that is more stable. There is emerging evidence of non-linearities in response (such as greater-than-expected mortality due to heat waves) as climates become more extreme. [11.3, 11.5]

The most important effect of climate change is that it will exacerbate current risks to health. *[very high confidence]* Although new infections and other conditions may emerge under climate change *[low confidence],* the largest risks by far will apply in populations already most affected by climate-related diseases. Thus, for example, the risks of under-nutrition from climate change will fall mainly on populations already experiencing under-nutrition. [11.3]

The most effective adaptation measures for health in the immediate term, therefore, are programs that extend basic public health measures and essential health services, increase capacity for disaster preparedness and response, and alleviate poverty. [11.6] *[very high confidence*]

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. Changes in temperature, rainfall and sea-level have altered distribution of some disease vectors, increased heat wave casualties, and reduced food production for vulnerable populations. *[moderate confidence]* [11.4]

If climate change continues as projected in scenarios in the next few decades, the major increases of ill-health compared to no climate change will occur through:

- Greater incidence of injury, disease, and death due to more intense heat waves, storms, floods, and fires. [11.4] *[very high confidence]*
- Increased risk of under-nutrition resulting from diminished food production in poor regions. [11.6] *[high confidence]*
- Loss of work capacity and reduced labor productivity in vulnerable populations [11.6] *[high confidence]*
- Increased risks of food- and water-borne diseases and vector-borne infections. [11.5] *[high confidence]*
- Modest improvements in some areas due to lower impacts of cold, shifts in food production, and reduction of disease-carrying vectors. These positive effects will be out-weighed, world-wide, by the magnitude and severity of the negative effects of climate change. [11.5] *[high confidence]*
- 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]* [11.7]

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*], accounting potentially for an economic impact of 1-2 trillion USD , depending on the economic valuation method used *[low confidence*]. [Box 11-4]

In the highest IPCC Representative Concentration Pathway, RCP8.5, by 2100 most of the world land area will be experiencing 4-7 degree higher temperatures than the recent past due to anthropogenic climate change. This means that important tipping points for health impacts may have been exceeded in many areas of the world during this century. These include sea level rise, storms, loss of agricultural productivity, and daily temperature/humidity conditions that exceed coping mechanisms, making potentially large areas seasonally uninhabitable for normal human activities, including growing food or working outdoors. [11.8] *[high confidence]*

There are opportunities to both reduce emissions of CAPs and at the same time improve local health in the communities that take action – in addition to the health protection for populations worldwide from climate change abatement. Among others, mitigation-related actions that will return health co-benefits as well include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy production and use in households and communities, through better combustion, energy efficiency, and a shift to cleaner renewable energy sources. [11.9] *[very high confidence]*
- Providing access to reproductive health services and thus improving child and maternal health through increased birth spacing, while reducing population growth and consequent CAP emissions over time. [11.9] *[high confidence]*

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) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that cause populations and individuals to be particularly susceptible 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.

Per IPCC guidelines, this is not a comprehensive, systematic review, but a scientific assessment based on the judgment of the authors. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field, through the multi-stage review process**.**

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 according to 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). At a regional level, inequalities in mortality have diminished, and convergence has been particularly marked amongst adults (Clark, 2011). Amongst children, mortality rates continue to fall, twice as quickly in the first decade of this century as in the 1990s (World Health Organization, 2011). The greatest decreases have occurred in urban areas and in wealthy parts of the world, and progress is uneven: more than 20 countries, mostly in sub-Saharan Africa, showed no reduction in child mortality between 1990 and 2006 (United Nations, 2010) (see Box 11-1).

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Box 11-1. Climate Change and the Millennium Development Goals

The Millennium Development Goals (MDGs) were established in 2000, as a way of focusing attention on some of the most pressing international development goals. Progress toward many of the goals, which are to be accomplished by 2015--and any subsequent related development efforts--will be affected by climate change. For example, Goal 4 states that the world community should "reduce by two thirds, between 1990 and 2015, the under-five mortality rate."[1] Figure 11-1 shows the current trends in reduction in child mortality worldwide by cause and indicates how far they are expected to fall above the MDG reduction goal by 2015. Each color represents a different child-mortality "disease wedge" with different risk factors and interventions. It also indicates overall how much faster they together must decline if the MDG is even to be reached ten years late, i.e., by 2025. According to the scenarios reported by WG1, the greatest impacts of climate change will occur after this date (ie mid-century). There are three ways climate change interacts with these wedges:

1) Two of the major causes of child mortality, diarrhoeal diseases and malaria, are directly influenced by the changes in temperature and rainfall to be expected with climate change (11.5.2; 11.5.1), probably making their reduction more difficult as climate change proceeds.
2) Malnutrition/under-nutrition is a major contributor to all the child-mortality wedges represented here, and will be more difficult to control as climate change proceeds (11.6.1)
3) On a more positive note, improving combustion of solid-fuel in poor households will both help reduce one of the major wedges, acute respiratory illnesses, and mitigate climate change through reduction in CAPs, a co-benefit (11.9.1).

[FOOTNOTE 1: http://www.un.org/millenniumgoals/childhealth.shtml]

[INSERT FIGURE 11-1 HERE
Figure 11-1: Climate change acts against human development: to reach the Millennium Development Goal for child mortality, the reduction in climate-sensitive causes of death at an early age must accelerate. Projected child mortality, 2008-2030, including climate-sensitive causes. Sources: Mortality projections by cause from WHO. Population projections from UN DESA. Child mortality rates from IGME. (World Health Organization, 2008a; Interagency Group for Child Mortality Estimation, 2011; United Nations, Department of Economic and Social Affairs, Population Division, 2011).]

_____ END BOX 11-1 HERE _____

Health Adjusted Life Expectancy (HALE), a measure that incorporates premature mortality and years of healthy life lost due to disease and injury, has also improved substantially, world-wide, but with big differences between countries. For instance, in 2010 male HALE was 27.9 years in Haiti and 68.8 years in Japan (Salomon *et al.*, 2012). (World Health Organization, 2009a; World Health Organization, 2010; World Health Organization, 2011a)Not all indicators are positive. For instance, child under-nutrition, implicated in about a third of all deaths under 5 years, increased in some countries between 2005 and 2008, and about 180 million children world-wide are stunted (short for their age) as a consequence (World Health Organization, 2010).

For specific causes of death, the patterns differ widely by region. The dramatic decline in cardiovascular disease in high-income countries is not seen in parts of the world that are developing rapidly, such as India and China. In those countries, the numbers of deaths from heart disease and stroke are increasing for two reasons; ageing populations and prevalent risk factors such as high blood pressure and cigarette smoking (Samb *et al.*, 2010). Cancer, diabetes, overweight, obesity, and mental disorders such as depression are also reported more commonly than previously in many low and middle income countries (Finucane *et al.*, 2011).

Most researchers anticipate mortality rates will continue to fall world-wide, and WHO estimates the total burden of disease (measured in DisabilityAdjusted Life Years per capita) will be cut by as much as 30% in 2030, compared with 2004 (World Health Organization, 2008b; World Health Organization, 2008c). These projections assume that economic and social development continue without interruption, particularly among poor populations, and as already noted, the global figures are dominated by trends in a few large countries (China and India in particular) (Mathers and Loncar, 2006). The underlying causes of poor health are expected to change substantially, with much greater prominence of chronic diseases and injury, largely due to changes in population structure. On its "baseline development" scenario, WHO projects the top three causes of burden of disease in 2030, world-wide, to be depression, ischemic heart disease and road traffic accidents (World Health Organization, 2008c).

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). We ran the same search protocol once more in January 2013 and found the number of citations per annum continued to grow after 2009, but at a slower rate. In addition, there are 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 (The World Bank, 2010), the Climate Vulnerability 2010 report (DARA, 2010), and the 2011 UN Habitat report on cities and climate change (United Nations Human Settlements Programme, 2011). Many of these publications were reviews and commentaries, and a smaller number of quantitative studies linking climate change and health. One review of the scientific literature from 2008 to 2011 identified 40 studies of this latter kind, most focused on high-income countries (Hosking and Campbell-Lendrum, 2012).

Since the AR4, there have been improvements in the methods applied to investigate climate change and health. They 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 11-2).

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Box 11-2. 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 collaborative study from sub-Saharan Africa and Asia. The INDEPTH Network currently has 43 members in 20 countries in Africa, Asia and Oceania. Using standardized health and demographic surveillance systems members have collected information on births, migration and deaths by cause over an average of 20 years.[2] Currently, there are about 3.4 million people under surveillance.

To study long-term relationships between weather and health, the authors collected information on all deaths occurring in 11 INDEPTH populations between 1 January 2000 and 31 December 2009 contributing about 10 million person-years of observation over 10 years (Diboulo *et al.*, 2012). Time dependent methods were used to relate meteorological data to health outcomes. Seasonality in mortality varies between age groups, and there are differences in susceptibility to weather related factors by gender. In the elderly population deaths related to dust storms and heat have been more pronounced compared with other ages. For example, in Nounain Burkina Faso, the relative risk of dying for the elderly above 60 years is associated with the temperature on the day preceding the death, as shown in Figure 11-2.

[INSERT FIGURE 11-2 HERE
Figure 11-2: Relationship between the risk of dying and average temperature on the preceding day, persons aged over 60 years, Nouna, Burkina Faso. Y-axis: log(RR), X-axis: Temp in °C, lagged by one day. Dotted lines show 95% confidence limits. Source: Diboulo et al, 2012.]

[FOOTNOTE 2: http://www.indepth-network.org]

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Since AR4, studies of the ways in which responses to climate change may affect health, so-called "co-benefits," have multiplied (Haines *et al.*, 2009). There has been growing interest also in effects of greenhouse emissions other than climate change. A prime example is ocean acidification (Doney *et al.*, 2008).

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. (Gething *et al.*, 2010; Béguin *et al.*, 2011)) 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 (Princeton Study, 2013).

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. There are potentially implications for human health such as malnutrition 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 are also constituents of air pollution, and have major effects on human health. See section 11.5.3 and Box 11-4.

11.2. How Climate Affects Health

There are three basic pathways by which climate change affects health as illustrated in Figure 11-3. These provide the organization for the chapter.

- **Direct impacts**, which relate primarily to heat, weather extremes, and floods that directly impact human health and safety. [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, malnutrition, refugees, and mental stress. [11.6]

[INSERT FIGURE 11-3 HERE
Figure 11-3: Ways in which climate, climate variability and climate change may influence human health.
Source: E. Garcia (2011).]

To a considerable extent, the health impacts in each of these categories could be greatly ameliorated by efforts to improve infrastructure, public health services, disaster management, and poverty alleviation, although at considerable cost and effort. There is another category of impacts, however, that would be much more difficult to deal with:

- **Lower probability extreme climate regimes** beyond 2050 for which there seems no reasonable adaptation options. [11.8]

Before exploring what is known in each of these areas, however, we summarize what is known about vulnerability that affects all these types of impact.

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 (Chapter 19). In this section, we consider causes of vulnerability to ill-health associated with climate change and climate variability, including internal characteristics of the individuals affected, properties of the population in which these individuals live, and factors in the physical environment.

The background climate-related disease rate of a population is the best single indicator of the 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.

We have divided the causes of vulnerability into sections for convenience. In practice, these factors combine, often in 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. Low levels of parental education, for example, are consistently associated with higher child mortality in times of stress, whether it is military conflict, famine, or other natural disasters. 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). But the precise causes of vulnerability, and therefore the most relevant coping capacities, vary greatly from one setting to another. Vulnerability to heat, for example, varies spatially: the factors that are important in rural areas differ from those that put people at risk in cities (Reid *et al*., 2009). In a similar vein, severe drought in Australia has been linked to psychological distress and to food insecurity – 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 (The World Bank, 2010). The critical factors for Sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that are projected to worsen with climate change, sparse infrastructure and high dependence on natural resources. 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 (this includes roughly half the population of Vietnam, and nearly all of Bangladesh).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for losses caused by climate change (Samson *et al*., 2011). Those living in inland cities at mid- and low latitudes, where present-day temperatures are frequently close to tolerable maxima, will be more severely affected by further warming than people living at high latitudes (Kjellstrom *et al*., 2013). The inhabitants of low-lying coral atolls are exquisitely 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 in future drought, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik *et al*., 2008). In high-income countries, location remains an important measure of susceptibility to the adverse effects of climate change. For example, living within 100- and 500-year flood zones, or within 5 km of coasts subject to sea level rise have been proposed, in the United States, as indicators of vulnerability to flooding (Acosta-Michlik *et al*., 2008; English *et al*., 2009). Living in rural and remote areas confers increased health risk because of poor 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 (Zhou *et al*., 2008).

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 pathogen and vector. In the United States, as one example, arboviral diseases such as dengue and the encephalitides 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 viruses circulating in the population, pre-flooding (Keim, 2008). Schistosomiasis was present in parts of Portugal in the 1950s. However, disease control efforts have eliminated the microbe from local snail populations so that although there is a competent vector and climate projections indicate that both parasite survival and vector survival will be favoured by rising temperatures, the risk of schistosomiasis returning to Portugal is low (Casimiro *et al.*, 2006). On the other hand, the high prevalence of HIV infection in many populations in Sub-Saharan Africa multiplies the health risks of prolonged drought, which may lead to migration, family disruption, deepening poverty, and increased exposure to unsafe sex.

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, illness due to malaria, diarrhea, and malnutrition is presently concentrated amongst children, for reasons of physiological susceptibility. In principle, children are expected 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. In California, a study of summer mortality records for 1999-2003 reported a stronger association of heat and mortality among infants (aged less than 1 year) and those aged 65 years and over than other age groups (Basu and Ostro, 2008). Other studies have sought, but not detected, such an association (Kovats and Hajat, 2008). Malaria parasites in the blood are more plentiful and mortality from malaria is more common in childhood (from about 6 months to 3 years) due to less well-developed immune responses to infection with the plasmodium (Michon *et al.*, 2007). Children dehydrate more rapidly than adults when affected by diarrhoeal diseases, and case-fatality rates are correspondingly higher. In some circumstances, children may be protected from climate-related diseases. For instance, maternal antibodies lower the risk of dengue fever in children in the first year of life. Children are generally at greater risk when food supplies are restricted. Households with children tend to have lower than average incomes, and childhood is a particularly sensitive period for health and development (Cook and Frank, 2008). Young people are at risk of mental health-related climate change impacts because, unlike for physical illness, mental illness peaks in youth.

Older people are at greater risk from storms, floods, heat-waves and other extreme events, 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 stressful events. Chronic diseases such as diabetes and ischemic heart disease, for example, magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki *et al.*, 2009). People over 65 years are also more strongly affected by air pollution due to ozone and other photochemical oxidants (Medina-Ramon *et al.*, 2006).

Vulnerability is associated with gender but the relationship is complex (World Health Organization, 2011b). In the United States, it is reported that males are at greater risk of death following flooding, perhaps because in this setting they are more commonly exposed to risk (e.g. many of the flood drownings in the US are motor-vehicle related, and on average, in this country, males drive more than females do) (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 heatwave, females were more affected than males in every age group except those aged 25-64. In this instance, the male dominance in the working age group may be related to differential exposures to heat in occupational settings. In Bangladesh, females are more affected than males by a range of climate hazards, at least in part because a greater proportion suffers from poverty and poor nutrition, and women are more frequently exposed to water-logged environments (Neelormi *et al.*, 2009). There may also be physiological differences in resilience.

After controlling for differences in age and co-morbidities, it appears that females are more strongly affected than males by high temperatures (Yu *et al*., 2010) and ozone air pollution (Medina-Ramon and Schwartz, 2008). There are signs also that 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 (Jamieson *et al*., 2006)(van Kerhove et al, 2011).

11.3.4. Socioeconomic Status

Socioeconomic status typically is measured by educational attainment, occupational prestige and personal income. At a national level, the poorest countries are most susceptible to damage caused by climate change, including health effects. Likewise, individuals and households most vulnerable to climate hazards are those with relatively low socioeconomic status. A review of global trends in tropical cyclones found that mortality risk depended on storm intensity, effective governance, and levels of poverty (Peduzzi *et al*., 2012). 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. This was explained partly by financial obstacles to relocation and other coping strategies, but there were differences also in knowledge of hazards and in beliefs about the preventability of flooding (Brouwer *et al*., 2007).

Occupation is also directly related to vulnerability to climate variability and extremes. For instance, outdoor occupations, which tend to have low socio-economic status, have been linked with disease and injury caused by flooding in China (Abuaku *et al*., 2009) and heat-waves in the United States (Centers for Disease Control and Prevention, 2008). Tawatsupa et al (2010) report differences in Thailand in the impacts of heat in the workplace in relation to socio-economic status. High socioeconomic status is not always protective: Singapore is one of the wealthiest countries in Asia, but in the 2000s experienced a resurgence of dengue fever, despite a considerable investment in vector control (Egger et al, 2008). In Brisbane, Australia, heat-wave mortality was related to age and gender, but not to small area measures of social disadvantage (Yu *et al*., 2010). This null finding, contrary to what has been observed elsewhere with individual-level measures of SES, (Medina-Ramon *et al*., 2006) may be due to the much greater variability in housing quality in Australia within neighborhoods than exists between neighborhoods, or the relatively flat social gradient in access to protective factors such as air conditioning and private transport.

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) to financial circumstances (for instance, lower incomes may restrict access to air conditioning during heat-waves), (Ostro *et al*., 2010) or to community-level characteristics (such as higher local crime rates or disrupted social networks). 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). Climate change in the North-West of Alaska led to increased vulnerability to accidents, diseases, mental stress, and food insecurity. Increase in temperature in the traditional ice cellars used for storage of fish and meat of sea mammals increases risks of food-borne and gastrointestinal diseases (Brubaker, M., Berner, J., Chavan, R., Warren,J., 2011). In Australia, indigenous peoples experience higher rates of diarrheal diseases and other climate-sensitive conditions than the remainder of the national population and their general health status is poorer, which places them at additional risk of climate stressors such as heat-waves (Petheram *et al*., 2010). They also experience greatly elevated rates of mental illness, suicide (Hunter, 2009) and related health behaviours, and these create substantial underlying vulnerability to climate change (Berry *et al*., 2010a)(Berry, 2009).

11.3.5. Public Health and Other Infrastructure

The physical environments around where people live and work can influence the health risks due to climate variability and climate change. 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). A study of the city of Phoenix, in the US, found the number of heat distress calls during heat waves was higher in areas affected by the urban heat island effect (which was measured by the proportion of impervious surfaces and minimum night time temperatures) (Uejio *et al*., 2011).

11.3.6. Projections for Vulnerability

Population growth may be one of the strongest influences on vulnerability to the health effects of climate change. Increasing numbers of people, in locations that are already resource-poor and are affected by climate risks, will magnify harmful impacts. Most of the projected growth in populations will occur 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 (< 100 L per person per day of sustainable freshwater flows) and in 50 years, unless there are rapid improvements in urban environments, demographic growth will push the number affected by chronic water shortages to around a billion (McDonald *et al*., 2011). Under a “business as usual” scenario, 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. 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). Overweight and obesity, associated with relatively poor heat tolerance, are becoming more common in most countries, and this trend is expected to continue (Finucane *et al*., 2011).

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 and 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 the HDI, 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). The relation between national wealth and health is roughly log linear, suggesting that an extra dollar buys more health gain in low-income countries than in medium and high income settings. It is notable also that the protective effects of national wealth are related to the severity of climate extremes. Peduzzi (2012) found “that poverty levels are less significant when facing very intense tropical cyclones, whereas at the lower intensities only the poorest suffer heavy losses.”

11.4. Direct Impacts of Climate Meteorological Changes on Health

11.4.1. Heat and Cold Extremes

Although there is strong evidence for the effects of variation in weather and season on a range of health outcomes, assessment of health impacts of observed climate change in the last few decades is challenging. Over the multi-decadal time scales that are necessary to measure climate change, the constellation of factors that influence disease rates is strongly affected by many other social and environmental factors. This means that robust studies require not only long time series of data on climate and disease rates, but also information on all other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. To complicate matters further, wherever risks are identified, health agencies are mandated to intervene immediately, confounding long-term analyses. Finally, there is no clear consensus on appropriate methods and standards for studies correlating long-term time trends in environmental variables and health outcomes. Such studies are therefore relatively rare, and seldom conclusive.

Since AR4, there is stronger evidence both for increases in some meteorological exposures that are hazardous to human health, and of attribution of these changes to anthropogenic influences. The IPCC Special Report on Extreme Events SREX [to be updated with data from AR5 WG1] 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.

In some cases, the connection between meteorological hazards and health impacts is sufficiently direct to draw strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between unusually hot days (defined as departures from average daily maximum temperatures for a specified location and date over 20 or 30 year baseline period) and increases in mortality is very robust (see studies reviewed in section 11.2.2 above). The observed *very likely* increase in daily maximum temperatures is therefore *likely* to have caused an increase in the number of heat-related deaths in mid-latitude populations. The decrease in minimum temperatures may have contributed to a decline in deaths associated with cold spells in the same populations, but there is no strong evidence in the literature so far. Moreover, the influence of seasonal factors other than temperature on winter mortality suggests that heat impacts on health may outweigh the benefits of fewer cold days (Kinney *et al*., 2012; Ebi and Mills, 2013). Quantification globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and those which do exist 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. For other extreme events and weather disasters (such as floods or drought), there is no good evidence of a climate change signal (IPCC, 2012).

11.4.1.1. Mechanisms

It is physiologically plausible that circulatory diseases are more common at high temperatures; for instance, displacement of blood to the skin surface may lead to circulatory collapse. In this regard, indoor thermal conditions are important, including ventilation, humidity, radiation from walls or ceiling and the presence or absence of air-conditioning, but these variables are seldom well-measured in epidemiological studies (Anderson *et al*., 2012). Biological mechanisms are less evident for other causes of death that have been related to weather. For instance, there is an association of ambient temperature with suicide (Page *et al*., 2007; Likhvar *et al*., 2011; Kim *et al*., 2011).

Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of physiologic tolerance to temperature (D'Ippoliti *et al*., 2010; Anderson and Bell, 2011), although the added effect is relatively small in some series, and most evident with prolonged heat waves. (Gasparrini and Armstrong, 2011) 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 genuinely 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. The reports from France (Fouillet *et al*., 2008)concluded that a very large proportion of the extra deaths occurred in elderly people (80% above age 75). However, heat wave-related mortality in younger ages was also substantial (approximately 3,000 deaths). 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). This relationship between risk factors in winter and summer time may complicate the attribution of heat and cold effects (e.g. with climate change), given their inter-dependence; milder winters may leave a higher proportion of vulnerable people, and predispose to a stronger subsequent summer heat effect (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 (McMichael *et al*., 2008; Bell *et al*., 2008b; Pudpong and Hajat, 2011).

Studies of temperature-related morbidity, most commonly based on hospital admission or emergency presentations, find increases particularly in cardio-vascular, respiratory and kidney diseases. (Hansen *et al*., 2008; Lin and Chan, 2009; Knowlton *et al*., 2009). Rapid changes in temperature may upset the balance between humans and parasites. It has been proposed that the speed with which organisms adapt to changes in temperatures is broadly speaking a function of mass, and in support of this proposition, 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 carrying out physical activity. The intra-body surplus heat created by physical activity causes particular vulnerability to heat effects in these population groups. This has importance for recreational physical activity outdoors and it is of special relevance to analysis of the impacts of climate change on occupational health (see separate section below) (Ebi and Mills, 2013). Since the association between unusually hot days and increases in mortality is so well documented, it is possible to conclude that an observed increase in daily maximum temperatures is *likely* to have caused an increase in the number of heat-related deaths. The decrease in minimum temperatures may have contributed to a decline in deaths associated with cold spells in the same populations. There are very few studies of the large developing country populations in the tropics, and those which do exist 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.

11.4.1.2.Near-Future Impacts

Under predicted climate change scenarios, it is likely heat waves will increase in frequency and intensity and worsen heat-related exposures, although acclimatization and improvements in energy efficiency may mitigate some of these effects (Wilkinson *et al*., 2007a; Wilkinson *et al*., 2007b; Bi and Parton, 2008; Hanna *et al*., 2011; Maloney and Forbes, 2011). In Australia, the number of “dangerously hot” days, when core body temperatures may increase by ≥ 2ºC and outdoor activity is hazardous, is forecast to rise from the current 4 to 6 days per year to 33-45 days per year by 2070 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 (Kinney *et al*., 2012; Ebi and Mills, 2013). Overall, the increase in heat-related mortality is projected to outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson *et al*., 2007b). A study of three Quebec cities projected 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, using years of life lost as the outcome, and located in Brisbane, Australia, found the gains associated with fewer cold days were outweighed by the effects of more hot days when warming exceeded 2ºC. (Huang *et al*., 2012). The same trend is reported for New York City: by the 2050s, premature mortality due to heat is projected to increase by 70% (Knowlton *et al*., 2007). It is not certain how rapidly populations may adjust to increased heat. In New York, it was estimated that acclimatisation may reduce the impact of added summer heat by roughly a quarter (Knowlton *et al*., 2007).

11.4.2. Floods

In the IPCC Fourth Assessment Report, floods were reported to be the most frequent natural weather disaster. This is still true; in 2010, the ten most important disasters, judged by the number of people affected, included six floods and these floods accounted for more than 90% of the total number of victims, i.e., 175 million people (Guha-Sapir *et al*., 2011). Most of the losses occurred in mid- to low-income countries such as China, Pakistan (Dar *et al*., 2011), Thailand, Cambodia, India, and Colombia. For instance, in 2007 flooding along the southern coast of Mozambique affected 285,000 people, caused 140,000 to be displaced from their homes, and led to 29 deaths (World Bank, 2011). However, as exemplified by severe, damaging floods in Australia in 2010 and in the north-east of the United States in 2012, developed countries are not immune. (Guha-Sapir *et al*., 2011; Powell, 2012).

Mechanisms

The direct impacts of storms and floods include drowning, injuries, hypothermia and infectious diseases, whereas indirect health effects result from damage to infrastructure and water supplies, displacement of people, and disruption to people's lives (Jonkman and Kelman, 2005). Over the last 10 years, floods in Europe have killed more than 1,000 people and affected over 3.4 million. Worldwide, it is estimated that two thirds of flood deaths are due to drowning, and 70% of flood-related deaths are male (Jonkman and Kelman, 2005).

The attribution of deaths to flood events has been found to be complex with immediate traumatic deaths being most easily recorded (WHO/HPA, 2012). There is some uncertainty as to whether flood events are associated with a longer-term effect on mortality in the flooded population (Milojevic *et al.*, 2011). A study in rural Bangladesh found no effect on flooding on subsequent diarrhoeal disease, but a small increase (RR 1.25) in acute respiratory infections (Milojevic *et al.*, 2012). Another report on Bangladesh found no evidence of increased risk of mortality or diarrhea during 3 years after flooding (Milojevic *et al.*, 2012).

Flood-related injuries have been caused when people are evacuating from flood waters, attempting to save family or valuables, or during the clean-up process (Schnitzler *et al.*, 2007; Jakubicka *et al.*, 2010). Drinking water can become contaminated by bacteria, sewage, agricultural waste or chemicals (CDC, 2011). Infectious diseases and vector mosquitos for malaria or dengue fever may also be affected by floods (Kouadio *et al.*, 2012). In many countries, heavy rainfall and flooding have led to outbreaks of leptospirosis (caused by contact with bacteria of the genus *Leptospira*, an organism which circulates in a wide variety of animal hosts, including rats) (Lau *et al.*, 2010). Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). A study of the aftermath of the 2007 England and Wales floods found that the prevalence of mental health symptoms (including psychological distress, anxiety and depression) was two to five times higher among individuals who reported flood water in the home compared to individuals who did not (Paranjothy *et al.*, 2011). In Taiwan, a survey conducted 3 months after Typhoon Markot found the prevalence of Post Traumatic Stress Disorder was 25.8% among 271 evacuated school children (Yen *et al.*, 2011).

We found no studies of near-future impacts of storms and flooding published since AR4.

11.4.3. Ultraviolet Radiation

Ambient UV levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers. 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 by 2% for each 1°C (van der Leun *et al.*, 2008). Higher temperatures in the northern countries and countries with temperate climates may result in an increase in the time which people spend outdoors and, thus in additional UV-induced-adverse effects. Notably, however, skin cancer rates are rising already in many countries, for other reasons, such as changes in travel and recreation.

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 infected insects such as mosquitoes or ticks. These are perhaps the most well-studied of the 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.

[INSERT TABLE 11-1 HERE
Table 11-1: Vector-borne diseases.]

11.5.1.1. Malaria

Malaria is mainly caused by four distinct species of plasmodium parasite (Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae, Plasmodium ovale), transmitted between individuals by Anopheline mosquitoes. In 2010 there were an estimated 216 million episodes of malaria world-wide, causing 655,000 deaths, mostly of children under 5 years in the African Region (WHO, 2011). World-wide, there have been significant advances made in malaria control in the last 20 years (Feachem, 2011), but the disease persists and is a challenge, particularly, in Africa. For example, large outbreaks have occurred in highland regions in East Africa, and these may have been promoted, at least in part, by rising temperatures locally (Chaves and Koenraadt, 2010).

The influence of temperature on malaria development appears to be non-linear, and is vector-specific (Alonso *et al*., 2011). Daily minimum temperature fluctuation acts to speed up parasite development, whereas variations around the maximum temperature tend to slow processes down (Paaijmans *et al*., 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *Anopheles 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 life cycle of the vector and the parasite: a study in one county of central eastern China reported that malaria incidence was related to maximum temperature and average humidity one month prior to identification of the case (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 factors such as levels of drug resistance and intensity of vector control programmes. Earlier research had failed to pick out a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer time periods have confirmed increasing temperatures since the 1950s (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 (Pascual *et al*., 2006; Alonso *et al*., 2011). A detailed 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 is likely to have facilitated malaria transmission, 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.

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. Estimates for the population at risk range from 30% to 54.7% of the world's population (2.05–3.74 billion). Three quarters of the people exposed to dengue are in the Asia-Pacific region. The disease is associated with climate on spatial (Beebe *et al*., 2009; Russell *et al*., 2009; Li *et al*., 2011), temporal (Hii *et al*., 2009; Hsieh and Chen, 2009; Herrera-Martinez and Rodriguez-Morales, 2010; Earnest *et al*., 2011; Gharbi *et al*., 2011; Pham *et al*., 2011; Descloux *et al*., 2012) and spatiotemporal (Chowell *et al*., 2008; Chowell *et al*., 2011; Lai, 2011) scales.

The principal vectors for dengue, *Aedes aegypti* and *Aedes albopictus* are climate-sensitive. Over the last two decades, climate conditions have become more suitable for *albopictus* in some areas (eg over central northwestern

Europe) but less suitable elsewhere (eg over southern Spain) (Caminade *et al*., 2012) Distribution of *Aedes 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. (Lu and Lin, 2009; Li *et al*., 2011)**.** A study in Dhaka, urban 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 11-3 HERE _____

Box 11-3. Case Study: Dengue Fever

Dengue Fever (DF) and its haemorrhagic manifestations are caused by four antigenically distinct serotypes (1 to 4) belonging to the Flaviviridae family. Each year within the “dengue belt” (between 35ºN and 35ºS latitude) there occur about 50-100 million cases of Dengue Fever and 500,000 cases of Dengue Haemorrhagic Fever (DHF) and Dengue Shock Syndrome (DSS) (Chadee *et al*., 2007). Prior to 2006, no consistent patterns had been reported in the seasonal distribution of DF and *Ae. aegypti* adult populations within the Americas. However, seasonality in dengue transmission is well known in South East Asia, with transmission occurring mostly during the wettest months of the year (Gubler and Kuno, 1997; Chadee *et al*., 2007).

Figure 11-4 shows most DF cases in Trinidad (80%) were recorded during the wet season when the *Aedes aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control programme 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 11-4 HERE
Figure 11-4: Rainfall, temperature, Breteau index (number of water containers with *A. aegypti* larvae per 100 houses), and dengue cases, Trinidad (2002-2004). Source: Chadee *et al*. (2007).]

Recent climate change scenarios for the period 2071-2100 project altered dynamic circulation patterns in both dry and wet seasons, therefore changing the intensity and frequency of rainfall events (Campbell *et al*., 2011). In addition, projections include 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 11-3 HERE _____

11.5.1.3.Tick-Borne Diseases

These include tick-borne encephalitis (TBE) and *Lyme borreliosis* (LB). TBE, is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Western Siberia has the highest incidence of the disease in the world. Asian countries affected by TBE include China, Japan, Mongolia, and South Korea. 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 found that climate may have an influence on the distribution of tick-borne diseases (Okuthe and Buyu, 2006; Lukan *et al*., 2010; Tokarevich *et al*., 2011; Estrada-Peña *et al*., 2012; Andreassen *et al*., 2012)**.**

In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996 to 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.

Studies since AR4 have confirmed a marked rise in TBE cases since 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. Variations in illness rates across the region demonstrate that climate change alone cannot explain the increase, and socioeconomic changes (including changes in agriculture and recreational activities), have strongly affected patterns of disease (Sumilo *et al.*, 2008; Randolph, 2010). In the Czech Republic, between 1970 and 2008, there are signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz *et al.*, 2012). However, the complex ecology and epidemiology of tick-borne diseases such as *Lyme borreliosis* 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). Plague, one of the oldest diseases known to man, remains endemic in many natural epidemic foci around the world. Outbreaks have been linked to seasonal and inter-annual variability in climate (Stenseth *et al.*, 2006; Nakazawa *et al.*, 2007; Holt *et al.*, 2009; Xu *et al.*, 2011). Chikungunya fever is another climate-sensitive mosquito-transmitted viral disease, (Anyamba *et al.*, 2012) first identified in Africa, now present also in Asia, and recently emerging in parts of Europe (Angelini *et al.*, 2008).

11.5.1.5. Near-Future Impacts

Using the A1B climate change scenario, Béguin et al. (2011) projected differences in the population at risk of malaria to 2030 and 2050. If there was no change in GDP per capita, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. The additional malaria transmission areas are shown in red in Figure 11-5. Keeping climate constant, and assuming strong and equitable economic growth, would lead to 1.74 billion people at risk (approximately half the present number at risk). 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.

[INSERT FIGURE 11-5 HERE
Figure 11-5: Contraction of the area of malaria transmission if economic development progresses as forecast (top panel, in blue); expansion in areas of transmission through higher temperatures (bottom panel, in red). Based on IPCC scenario A1B, projections to 2050. Source: Béguin *et al.* (2011).]

There are no studies that project the return of established malaria to Northern America or Europe, where it was once prevalent. Although suitable vectors for *P. vivax* malaria abound in these parts of the world, the risk of re-introduction is thought to be very low, barring civil strife or a breakdown of health services.

We could identify only one study published since 2006 that models future risk of dengue under climate change. Åström (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. Three global circulation models were run to 2050, at which time, 4.86 billion people were projected to live in areas at risk of dengue - 6.1% or 280 million more than would have been expected otherwise. Under scenarios of high GDP growth, the number exposed to dengue in 2050 falls to 4.46 billion, ie 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 concentrated by bivalve shellfish (e.g., oysters) or deposited on irrigated food crops. Pathogens of concern for waterborne exposure may be enteric and transmitted by the fecal oral route (enteric viruses, bacteria and protozoa) or may occur naturally in aquatic systems (bacteria and protozoa). Climate may act directly by influencing growth, survival, persistence, transmission or virulence of pathogens; indirect influences include climate-related perturbations in local eco-systems and/or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrio

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Although cholera is unique in that it can be transmitted both by drinking water and by environmental exposure in seawater and seafood, other Vibrio species are solely linked to seawater and shellfish. These primarily 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 (eg direct contact or via seafood).In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (e.g., (Paz, 2009; Islam, 2009; Reyburn *et al*., 2011)). In Bangladesh, precipitation has been shown to be predictive of cholera cases, and higher risk is associated with both high rainfall (and stream level) events as well as below threshold rainfall levels (and lower stream levels) (Hashizume, 2008). This bi-modal pattern is hypothesized to be due to increased water-washed contamination during heavy rains and decreased sanitation (and increased direct contamination) during drier events (Hashizume, 2008).

11.5.2.2. Enteric Bacteria and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011); however, with a few exceptions we do not know the specific cause of the diarrheal illness nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, which are among the most common zoonotic food and waterborne bacterial pathogens worldwide and both show distinct seasonality in infection and higher disease rates at warmer temperatures, especially when outbreaks are excluded. 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. Other studies have shown that when released into the environment, enterovirus persistence is negatively correlated with temperature (e.g., (Wetz *et al*., 2004)).

Temperature is directly linked with enteric disease risk in Arctic communities, where rising temperatures and loss of permafrost may result in transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources or other surface waters (Martin, D., B. Belanger, P Gosselin, J Brazeau,C.Furgal and S.Dery, 2007). Additionally, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008). Harper et al. (2011) showed that in coastal Arctic communities in Canada, higher temperatures precede reports of infectious gastroenteritis with high temperatures corresponding with a 3.9-fold increase in clinic visits within 3 weeks; however this trend was not statistically significant.

Rainfall has also been associated with enteric infections. Pathogens are more likely to be taken up by produce crops (eg lettuce) under conditions of both flooding and drought (Ge *et al*., 2012) and this is reflected also in patterns of illness (Bandyopadhyay *et al*., 2012). Higher concentrations of enteric viruses have been noted in drinking water (surface and ground) and recreational water following heavy rainfall (e.g., (Futch, 2010; Jofre *et al*., 2010)). Likewise, cases of hand, foot and mouth disease (echovirus 71 or coxsackievirus A16) in Singapore increase linearly with cumulative rainfall of up to 75 mm per week (Hii *et al*., 2011). In the Arctic (Canada), rainfall and increased snowmelt were associated with both deterioration in water quality in reservoirs (evidenced by fecal indicator bacteria) and increased clinic visits for infectious gastroenteritis (Harper *et al*., 2011).

Illness caused by infection with the rotavirus 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 (Turcios *et al*., 2006; Atchison *et al*., 2010) 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 (Tate *et al*., 2009; Pitzer *et al*., 2011).

11.5.2.3.Near-Term Future

Kolstand and Johansson (2011) project an increase of 8-11% in the risk of diarrhea in the tropics and subtropics due to climate change, up to 2039. In 2040-69 and 2070-99, Kolstad and Johansson projected risk increases of 15-20% and 22-29% respectively using the A1B scenario and 19 coupled atmosphere-ocean climate models from the World Climate Research Programme Coupled Model Intercomparison Project (CMIP3). This study did not projections for economic growth and social development.

Zhou *et al*. (2008) estimated the transmission of schistosomiasis due to *S. japonicum* in China based on rising temperatures in 2030 and 2050. They concluded that an additional 784 thousand km^2 would become suitable for schistosomiasis transmission in China by 2050 (Figure 11-6).

[INSERT FIGURE 11-6 HERE
Figure 11-6: Projected risk map of schistosomiasis*(S. japonicum)* transmission in China in 2050. For comparison the current risk map in 2000. Green area denotes the range of schistosomiasis in 2000. The blue area shows the geographic expansion. 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 Ch x 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 11-4.

_____ START BOX 11-4 HERE _____

Box 11-4. 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 done in recent years (e.g.(UNEP, 2011)), the most comprehensive was the Comparative Risk Assessment carried out as part of the 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 half a million 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 DALY terms, 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, ch 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 lower bound (World Health Organization, 2009b). 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.

Unfortunately, the twin goals of protecting health and climate do not always lead to congruent actions. All particles are dangerous for health, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith *et al*., 2009). Indeed, as indicated in WGI (Ch x), elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate. As discussed in the co-benefits section below (11.9), there are nevertheless specific actions that will work toward both goals.

_____ END BOX 11-4 HERE _____

Although there is a large literature on the health effects of particle air pollution (see Box 11-4), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way. Thus, we focus here on chronic ozone exposures, which are found in WGI (Ch x) to be enhanced in some scenarios of future climate change.

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 (US EPA, 2007). Therefore, if temperatures rise, many air pollution models (Ebi and McGregor, 2008; Tsai *et al*., 2008; Chang *et al*., 2010; Polvani *et al*., 2011) project increased ozone production especially within and surrounding urban areas (Hesterberg *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 even 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), ozone was 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 (WHO 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which may increase under climate change, release large amounts of particulate matter and other toxic substances that may affect larger numbers of people (Handmer *et al*., 2012; Finlay *et al*., 2012)**.** During a fire near Denver (USA) in June 2009, 1-hour concentrations of PM_{10} and $PM_{2.5}$ reached 370 $\mu g/m^3$ and 200 $\mu g/m^3$, and 24-hour average concentrations reached 91 $\mu g/m^3$ and 44 $\mu g/m^3$, compared to the 24-hour WHO air quality guidelines for these pollutants of 50 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively (Vedal and Dutton, 2006).

One study of world-wide 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 $5^{\circ}C$ or more for 45 days and 10 new temperature records were established in July and 9 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 $\mu g/m^3$ PM10 most days, but occasionally reached 1500 $\mu g/m^3$. The highest 24-h CO concentration was 30 mg/m^3 compared to the WHO AQG of 7 $\mu g/m^3$, and the levels of formaldehyde, ethyl benzene, benzene, toluene and styrene were also increased (State Environmental Institution "Mosecomonitoring", 2010).

There is an interaction of ozone and heat waves as well. Dear et al. (2005) modeled the daily mortality on heat and ozone during the European summer heatwave 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, allergic rhinitis, conjunctivitis and dermatitis (Beggs et al, 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 contains 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; Dong *et al.*, 2011; Chang *et al.*, 2012; Lepeule *et al.*, 2012; Meister *et al.*, 2012). High temperatures may also magnify the effects of ozone (Ren *et al.*, 2008; Jackson *et al.*, 2010). 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 (see Table 11-2; Bell *et al.*, 2007; Selin *et al.*, 2009; Tagaris *et al.*, 2009). Most studies focus on Europe, the U.S. and Canada. 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 get worse.

[INSERT TABLE 11-2 HERE
Table 11-2: Projected future health impacts of climate change through air pollution.]

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Ren *et al.*, 2008; Jackson *et al.*, 2010). In general, all-cause mortality related to ozone is expected to increase in the US and Canada (Bell *et al.*, 2007; Tagaris *et al.*, 2009; Jackson *et al.*, 2010; Cheng *et al.*, 2011). 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).

A study that investigated regional air quality in the United States in 2050, using 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 O_3-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

At its most simple, nutrition can be considered as resulting from the interaction of three main elements: agricultural production (net of post-harvest wastes and storage losses), governance and human disease, especially those which affect appetite, nutrient absorption and catabolism (Black *et al.*, 2008; Lloyd *et al.*, 2011). Many of these factors are influenced by climate. Malnutrition, referring to insufficient nutrient intake, is also related very closely to a temporary or long-term ability to pay for sufficient food, i.e., poverty.

11.6.1.1.Mechanisms

See Chapter 7 for a discussion of the impact of climate change on agricultural production.

The magnitude of detected decline in land-based agricultural production due to increasing temperatures and changes in rainfall is small compared to the increase in harvests due to improved farming knowledge and technology (Lobell *et al*., 2011). It is also minor in comparison to the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished and wasted in other ways (Foley *et al*., 2011). 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 speculation (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011) and heatwaves have contributed to higher prices, which, all else being equal, will increase the number of malnourished people.

The modeling of past and future agro-climatic effects, even without considering their health impact, is a formidable challenge, and some argue the existing agro-climate models are excessively simple and biased toward the optimistic (Butler, 2010; Gornall *et al*., 2010). Moreover, the strength of the carbon fertilization effect (CFE) may have been overstated (Long *et al*., 2006; Leakey *et al*., 2008). Higher concentrations of CO_2 may also enhance the growth of pests (Ziska *et al*., 2009; Nelson *et al*., 2009; Nelson *et al*., 2010) and damage some crops, including cassava, a staple for about 750 million mostly poor people (Gleadow *et al*., 2009). These effects to date are generally not incorporated into models.

11.6.1.2.Near-Term Future

Since AR4 four studies have been published which project the effect of climate change on food availability (undernourishment) and malnutrition (acute and chronic).[3] It is important to distinguish between undernourishment (hunger), caused by lack of food, and malnutrition which is due not only to food intake but to other factors (eg chronic infections).

[FOOTNOTE 3: In technical terms, these are called “wasting” (acute) and “stunting” chronic. The former is measured as deviations from the weight for height, the latter from weight for age.]

Ebi (2008) projected the climate-attributable numbers of malnourished children to 2030 and reported a 10% (4,673,000 cases) increase against the counterfactual of no climate change. Nelson et al. (2009; 2010) built a global agricultural supply and demand projection model (IMPACT 2009) and a crop simulation model (DSSAT) to estimate crop production, with and without CO_2 enrichment. The authors projected per capita calorie under climate models from NCAR and CSIRO (the world projected in the former is wetter and dryer). The authors estimate that there would be about 25 million additional malnourished children in 2050 with climate change (Nelson *et al*., 2009), focusing on the effect of investment in agricultural productivity (see Table 11-3). In those parts of the world most affected by under- and mal-nutrition (Sub-Saharan Africa and the Middle East and North Africa), comprehensive investments in agriculture would reduce the anticipated impact of climate change, but not entirely.

[INSERT TABLE 11-3 HERE
Table 11-3: Number of malnourished children less than 5 years of age (in millions) in 2000 and under the NCAR climate model (using A2 scenario from AR4) till 2050. Assumptions for investment in agricultural productivity: + only in developing countries; ++ both in developing and developed countries. Results assume no CO_2 fertilization effects. Adapted from Nelson *et al*. (2009).]

Lloyd et al. (2011) built a model for estimating future undernourishment (too little food) and child malnutrition (stunting), under two climate change scenarios and a reference scenario without climate change. While the estimates of undernourished children were based on food availability projections from Nelson et al. (2009), stunting was modeled using “food” and “non-food” causes. The increase in severe stunting attributable to climate change in 2050 ranged from 31% in central Sub-Saharan Africa to 62% in South Asia. The comparison was a world without climate change, in which the numbers of undernourished and stunted children fell. The authors concluded that climate change will hold back efforts to reduce child malnutrition in the most severely affected parts of the world, even with allowances for economic growth.

In a subsequent paper, Lloyd et al. (2011) estimated the number of malnutrition-attributable childhood deaths. The relationship between severity of stunting and mortality was drawn from Black et al. (2008). For 2030, their model projected 108,028 malnutrition-related childhood deaths from climate change (8.0% out of a total of 1,256,440 malnutrition-related deaths). For 2050, they estimated this number to be 96,460 out of 614,361 (15.7%). Hence, while the absolute number of children dying from malnutrition would fall by half between 2030 and 2050 due to social and economic development, the proportion attributable to climate change would double.

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 small-for-age children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial investments in education and infrastructure.

In summary, we have high confidence that climate change will have a substantial negative impact on (i) per capita calorie availability, (ii) childhood malnutrition, particularly stunting and (iii) on malnutrition–related child deaths and DALYs lost (high agreement with medium evidence).

11.6.2. Occupational Health

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

11.6.2.1. Heat Strain and Heat Stroke

The basic processes of human thermoregulation are well-understood (Parsons, 2003). If the body temperature goes beyond 38°C, performance may be impaired. Temperature above 39°C risks symptoms of “heat stroke”: organ damage, loss of consciousness, and death. Pre-existing disease or malnutrition increases vulnerability. Experimental and field studies have documented the risks of excessive heat exposure (Ramsey and Bernard, 2000; Parsons, 2003) and detailed exposure response relationships were described long ago (Wyndham, 1969). Heat remains an occupational health issue even in a high-income country like the USA (Luginbuhl *et al.*, 2008). 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 stroke, hourly productivity goes down.

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 (Lecocq and Shalizi, 2007; Kjellstrom *et al.*, 2009a; Kjellstrom *et al.*, 2011; Kjellstrom and Crowe, 2011). Kjellstrom et al. (Kjellstrom *et al.*, 2009a; Kjellstrom and Crowe, 2011; Kjellstrom *et al.*, 2011) and Dunne et al. (Dunne *et al.*, 2013) estimate 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

Exposure to heat affects psychological performance (Hancock *et al.*, 2007) and increased risk of injuries (Ramsey, 1995). 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.

Another risk factor is increased chemical poisoning where solvents are used, because higher temperatures make the solvents evaporate faster and may lead to higher occupational exposures (Bennett and McMichael, 2010). In the Arctic, the part of the world that is now experiencing the fastest increase of temperatures, traditional hunting and fishing activities are affected by reduction in sea ice and there is a greater risk of drowning (Ford *et al.*, 2008).

11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Kjellstrom *et al.*, 2009b; Dunne *et al.*, 2013). 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 South East 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 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity loss, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom *et al.*, 2009a; Kjellstrom *et al.*, 2011).

11.6.3. Mental Health

Mental illness, a major contributor to the global burden of disease, (Mathers and Loncar, 2006) leads to functional impairment and disordered behaviour in domains as diverse as crime, housing, employment, relationships, violence, education, physical health, substance use and health behaviours. Poor mental health is associated in general with lower levels of resilience, coping and adaptive capacity. Overwhelmed by repeated disasters, an increasing numbers of people may lose hope, as appears to happen with farmers facing severe drought (Berry *et al.*, 2011).

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). For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Hanigan *et al.*, 2012; O'Brien *et al.*, Under review)(Alston, 2008).

Harsher weather conditions increase the stress on those who are already mentally ill, worsening their condition and prognosis; and may create sufficient stress for some who are not yet ill to become so (Berry *et al.*, 2010b). Functional impairment means diminished population-level resilience, adaptive capacity and coping. There may be impacts on agricultural productivity, fishing, forestry, tourism, mining, subsistence farming and other economic endeavours reliant on the land. As more than half the world’s population now lives in cities, disasters such as cyclones, heatwaves and major floods can easily stress or destroy infrastructure and take lives *en masse*, by affecting whole zones of cities. Here again, the vulnerable are most at risk: cities have zones of concentrated disadvantage (where mental disorders are disproportionately prevalent) (Berry, 2007) and these typically lie on the least advantageous land, land that is most prone to disaster (such as flood plains). Impacts on infrastructure and immediate loss of life, in turn, compromise local industries, businesses and households; and when these face extreme pressure, livelihoods, families and eventually whole communities can struggle to cope. Of particular importance, to the extent that deteriorating community functioning involves loss of social capital, mental health will be at risk because the presence of social capital is strongly protective for health, especially for mental health. (Berry *et al.*, 2010b).

The impacts of extreme weather events on mental health are broad-ranging: Major Depressive Disorder is the most common disorder, followed by Post-Traumatic Stress Disorder, other anxiety disorders and, mental distress. (Crabtree, 2012). A cyclone and flooding disaster in Queensland, in 2010-11 cost that Australian state US$7 billion in infrastructure repairs alone with consequences for livelihoods and health. Disadvantaged communities received the most damage to homes, businesses and incomes *and* reported higher rates of trauma-related impact per traumatic exposure than did less disadvantaged respondents (Clemens *et al.*, in preparation). That is, there was a linear dose-response effect for all victims but the response was significantly larger for disadvantaged communities. Two years later, another flood event affected that state before these same communities had recovered from the first.

In addition to indirect effects on mental health via the risk/disadvantage cycle, extreme weather events may adversely affect mental health *directly*, through immediate psychiatric trauma, heat impacts on certain classes of psychiatric medication), and 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 Population Displacement

A study in Milwaukee, Wisconsin reported temperatures above 27.2°C were associated with increased accidents and self-harm (Li, T., Horton, R., Kinney,P., 2011). In Adelaide, South Australia, assault-related injuries among 15–64 year-olds increased significantly during heat waves (Nitschke *et al.*, 2007), and others have reported a relationship between high temperatures and increased risk of suicide. (Page *et al.*, 2007). Changes in behavior in times of extreme temperatures, however, may reduce the risks of some forms of injury. For example, in South Australia a significant decrease in automobile accidents was found during heat waves in the 75+ age group (Nitschke *et al.*, 2007).

Soil degradation, freshwater scarcity, population pressures and other forces that are related to climate are all potential causes of conflict. A study of internal conflict in African countries from 1981-2002 found a positive correlation between country-level temperature increases and probability of armed conflict and suggested that the effects of temperature change on agriculture might be a significant factor (Burke *et al.*, 2010). The relationships are not straightforward, however, as many factors influence conflict and violence. A study drawing on data from 1960-99, including more than 160 countries, found that poverty, low economic growth and high dependence on primary commodity exports were strongly associated with civil war, while ethnic and religious diversity as well as democracy were not (Collier and Hoeffler, 2004). The resultant ambiguity has recently led to more highly specified models that take account of variables such as social networks, indigenous knowledge and family cohesion that reduce vulnerability to climate disasters (Adger *et al.*, 2003). In Sub-Saharan Africa it has been reported climates that are more suitable for agriculture are associated with a lower risk of conflict (Hendrix and Glaser, 2007). Another study argues that environmentally induced migration can increase the risk of conflict, particularly in less-developed countries, and the risk is compounded by rapid population growth and limited migration opportunities (Reuveny, 2007).

Impacts of drought on human health also occur largely through indirect pathways; such as impacts on agriculture and population displacement (MacDonald, 2010; Kolmannskog, 2012).

Although the relationship between climate and armed conflict should not be overstated, in view of other social, cultural, political and economic factors that play a part, there is ample evidence that the depletion and altered distribution of natural resources may heighten the risk of violent conflict (Brauch, 2002; Oberthür *et al.*, 2002). Using data from 1950 to 2004 from the tropics, Solomon et al. (2010) found that the probability of new civil conflicts arising doubles during El Niño years relative to La Niña years. A study of a thousand years of violent conflict in Europe and various reconstructions of temperature and precipitation, found that conflict was exacerbated during cold periods that were associated with crop failures and food shortages (Tol and Wagner, 2010). Similar findings have been reported in China (Zhang *et al.*, 2006), and indeed the links between rapid climate change, starvation and civil disorder and collapse are apparent as far back as the first agricultural settlements roughly 10,000 years before the present (McMichael *et al.*, 2012).

11.7. Adaptation to Protect Health

Life expectancies and years of healthy life have increased considerably over the past century due to improvements in public health and health care strategies, policies, and measures, due to greater understanding of the complex factors driving adverse health conditions, as well as actions in other sectors, such as providing access to safe water and improved sanitation. In some situations, climate variability and change threatens continuing advances in reducing the burden of climate-sensitive health outcomes. The degree to which programs and measures will need modification to address any additional pressures from climate change will depend on factors such as the current burden of climate-sensitive health outcomes, the effectiveness of current interventions, projections of where, when, and how the 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 process of adaptation will be on-going adjustments to the degree and rate of climate change and other factors driving the incidence and geographic range of climate-sensitive health outcomes.

The scientific literature on adaptation to climate change has expanded since AR4, 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, 2012).

The value of adaptation is demonstrated by the population health impacts of recent disasters associated with extreme weather and climate events. For example, more than 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 5-10,000 deaths even though 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 both high technology information systems and relatively simple measures such as training volunteers who could 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 occurs when information on the risks of climate change is integrated into policies and measures, without changing underlying assumptions. This includes improving public health and health care services for climate-sensitive health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation occurs with changes in underlying assumptions, including shifts in attitudes and perceptions. This includes vulnerability mapping, early warning systems, and other measures. Transformation occurs with changes in social and other structures that mediate the construction of risk.

11.7.1. Improving Basic Public Health and Health Care Services

Because the baseline health status of a population may be the single most important predictor of the future health impacts of climate change and the costs of adaptation (Pandey, 2010), reducing background rates of disease and injury is an important step to improving population resilience and minimizing poor health outcomes from climate change.

Most health adaptation is focusing on improvements in basic public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring risky exposures, and facilitating coordination between health and other sectors to address shifts in the incidence and geographic range of diseases (Woodward *et al.*, 2011). An example is Lusaka, Zambia, where the incidence of cholera rises sharply following heavy rainfall, with lower risk in parts of the city with effective drainage networks (Sasaki *et al.*, 2009).

Health care interventions may reduce harm caused by climate and other environmental stressors. As one example, following the introduction of vaccination programs in the United States, 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 heatwaves 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). Similarly, diabetes care was compromised following Hurricane Katrina in the United States by a lack of blood glucose testing kits, and insulin and other diabetes medications (Cefalu *et al.*, 2006). 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. Another example is in Benin, where 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 designing into programs and measures considerations of how a changing climate could alter health burdens and the effectiveness of intervention actions. Ten “essential public health services” underpin coping with the health risks of climate change (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 are relevant as well, because communities with high levels of social capital tend to be more successful in disseminating health and related messages, ensuring compliance with behavioural norms and providing support to those in need (Frumkin *et al.*, 2008).

Vulnerability Mapping

Remote sensing technologies are now sufficiently fine-grained for mapping local vulnerability factors and can be used to guide interventions to reduce exposures and/or impacts. 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 heatwaves (Luber and McGeehin, 2008). 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 should consideration of 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 as a means of alerting public health authorities to climate-related health risks. Effective early warning systems take into consideration the wide range of factors that can drive risk.

Heatwave and health warning systems (HHWS) are designed to prevent negative health impacts. Components of an effective HHWS 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 heatwave and prevention responses, and evaluating and revising the system to increase effectiveness in a changing climate (Lowe *et al*., 2011). Of seven studies of the effectiveness of heatwave early warning systems to reduce heat-related mortality, six reported fewer deaths during heatwaves after implementation of the system (Palecki *et al*., 2001; Weisskopf *et al*., 2002; Ebi *et al*., 2004; Tan *et al*., 2007; Fouillet *et al*., 2008; Chau *et al*., 2009); only Morabito et al. (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures similar to those experienced during the 2003 heatwave, with about 2000 excess deaths. This was more than 4000 less than was anticipated on the basis of the experience in 2003. 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 heatwave early warning system (Fouillet *et al*., 2008). A review of the heatwave 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 action increase resilience (Lowe *et al*., 2011).

Early warning systems also have been developed using predictive models for vector-borne and food-borne infections. 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). The incidence of several bacterial enteric infections varies with ambient temperature (Fleury *et al*., 2006); this information has been used to develop health alerts based on projected temperatures. 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 play an important part in protecting against disease and injury resulting from climate change. EuroHEAT, a European review of public health responses to extreme heat, identified transport policies building design, and urban land use as important elements of national and municipal heatwave 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 heatwave-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 heatwaves than 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 programs designed for other purposes can facilitate adaptation. In the Philippines, for example, interventions in low-income urban settings 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). All these have the potential to reduce the harmful effects of climate extremes on health.

Migration

Migration is a common coping strategy in the face of adverse changes in climate, and may itself have significant effects on health, positive and negative (McMichael *et al*., 2012)(McMichael et al., 2010). Within the Pacific, there has been migration from outer islands to urban centers, partially due to environmental pressures, improving economic and educational opportunities for some. But there is a cost in infectious diseases and other health problems caused by crowding associated with a lack of adequate water supplies, waste disposal, and housing (Locke, 2009). Large numbers of Pacific islanders have also moved to countries around the Pacific rim and comparisons of the health of migrants and peers in the islands show mixed effects (higher levels of risk factors such as raised blood pressure and cigarette smoking among migrants, but also lower mortality rates overall and higher life expectancies). Climate-related migration includes the movements of population between countries, and within country shifts, such as flows to cities from drought and heat-affected rural areas (Acosta-Michlik *et al.*, 2008). Where people choose to live reflects a complex balance of risks and benefits. Where large numbers of people are forced to migrate at the same time, there may be considerable social, cultural, economic and health implications for receiving communities, particularly where these peoples may be traumatised (McMichael *et al.*, 2012). A study in Indore in India found that low-income households were willing to live in flood-prone areas because of other advantages provided by these sites, including access to health care and low-cost housing (United Nations Human Settlements Programme, 2011).

11.8. Limits to Adaptation: Low-Probability Extreme Climates

Most attempts to quantify health burdens associated with future climate change consider relatively short time horizons (e.g. 2030 or 2050) and modest increases in global average temperature, typically less than 2 degrees Celsius during the time frame considered. Because of the longevity of some greenhouse gases in the atmosphere and inertia of the climate system, emissions today will, however, contribute to warming far beyond 2050. Moreover, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above pre-industrial temperatures (Rogelj *et al.*, 2009; Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012). Therefore it is important to examine the likely consequences of warming beyond 2 degrees, what we have called high-end warming scenarios (New *et al.* 2011).

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 11-7). Nonlinear and threshold effects have been observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, In Press), agricultural crop yields, as key determinants of childhood nutrition and development (Schlenker and Roberts, 2009; Lobell *et al.*, 2011), and infectious diseases (Altizer *et al.*, 2006), for example. These are briefly elaborated here.

[INSERT FIGURE 11-7 HERE
Figure 11-7: Extreme warming by 2100 from RCP8.5. Mean temperatures above levels around 2000. Note higher effects over land. Source: WGI AR5 _____.]

11.8.1. Exceeding Adaptation Limits in High-End Warming Scenarios

The prospect of rapid and extreme levels of warming raises questions about the biological limitations to human adaptability. As discussed above, when the surrounding environment exceeds body temperature at high humidity, the body has limited capacity to lose excess heat, and over time the core temperature will rise with, eventually, fatal consequence.

Sherwood and Huber (2010) argue that humans cannot tolerate sustained periods of wet-bulb temperatures above 35°C. They 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 today's human population. While transformative adaptation measures such as underground settlements or "bubble cities" might make such conditions habitable for humans, present ways of life would become impossible.

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). (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.) Assuming no adaptation and a transition in the labor force from agricultural to more service and industrial occupations, Kjellstrom *et al.* (2009b) estimate that global mean warming of 3.4°C above preindustrial temperatures will lead to losses in labor productivity of 11-27% in Andean and Central America, Southeast Asia and the Caribbean. Dunne *et al.* (2013) estimate losses to global labor productivity under a similar degree of warming in an analysis that fixes the population distribution to that of 2010 and does not consider changes in the labor force. They estimate that, under the RCP 8.5 scenario in which carbon dioxide concentrations continue to rise through 2200, global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200.

Maloney and Forbes (Maloney and Forbes, 2011) use two heat balance models to examine the potential constraints heat will place on human activity in Perth, Australia in 2070. The authors consider a business-as-usual emissions scenario in which mean *regional* temperature increases by 6°C and assume temperature variability, relative humidity and wind speed mirror current conditions. They estimate that the number of days when heat balance will not be possible while undertaking moderate activity is estimated to increase from less than one to 11-23 days per year for acclimatized individuals, and from 13-14 to 56-60 days per year for unacclimatized individuals (ranges reflect the estimates derived from the two models). Heat stroke, an uncontrolled rise in core body temperature, would ensue in less than two hours for those performing physical labor on 15-26 days out of the year for acclimatized and 67-68 days out of the year for unacclimatized individuals, relative to 1-2 and 17-18 days out of the year at present.

Willett and Sherwood (2012) estimate future changes in summertime WBGT across 15 geographic regions. With regional warming of 5°C and assuming constant relative humidity, extreme prolonged heat events during which the 5-day average maximum WBGT is 35°C or higher are predicted to occur for over 90% of the summer in India, Northern Australia, Southeastern USA and the Caribbean, compared to current rates between 20-35%. It is projected that tropical and mid-latitude regions will be particularly badly affected, even though they will be warming less than the global average, due to greater increases in absolute humidity. Although the authors do not attempt to model the health impacts of such prolonged extreme heat, unprotected outdoor labor during the daytime in these conditions would be perilous for most of the summer.

11.8.2. Agricultural Limitations and Human Nutrition

Agricultural crops similarly have physiological limitations in terms of thermal and water stress. Analysis of six decades of late-spring barley yields in the Czech Republic show a strong and symmetrical inverted U-shaped relationship to rainfall and to temperature (Brázdil *et al.*, 2009). Beyond the climate tolerance range, yields decline rapidly with too much or too little heat or soil moisture. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures are essentially linear (Lloyd *et al.*, 2011; Lake *et al.*, 2012), reflecting uncertainties about non-linear parameter values, future extreme events and climatic thresholds for other influences such as infestations and plant diseases.

Experimental field studies by the International Rice Research Institute have estimated that rice yields decline by about 10% for each 1°C rise in overnight temperature during flowering (Peng *et al.*, 2004). Rice seed set is impaired at air temperatures above about 35°C (Yoshida *et al.*, 1981), although there is the potential to breed more heat tolerant cultivars (Matsui *et al.*, 2001; Jagadish *et al.*, 2010). Corn fails to germinate at about 40°C (Blacklow, 1972; Birch *et al.*, 1998). The lethal temperature for wheat appears to be about 47.5°C, while key phenological stages such as sowing to emergence and grain-filling have lower maximum temperature thresholds of 32.7°C and 35.4°C, respectively (Porter and Gawith, 1999; Porter and Semenov, 2005). For more information see Chapter 7, and recent reviews such as Texeira et al. (Teixeira *et al.*, 2011). Water insufficiency is likely to constrain agriculture under extreme warming in some regions. For example, failures of rain-fed crops due to lack of available water are predicted to occur once every two years in much of southern Africa with a 5°C global average temperature increase (Thornton *et al.*, 2011).

11.8.3. Infectious Disease Patterns under Extreme Warming

Substantial warming (above the global average) in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries. The northwards extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis respectively, provide a foretaste of how this can happen (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. Health Consequences of Displacement, Migration, and Social Conflict

More human migration can be expected under extreme levels of warming as adaptive capacity becomes overwhelmed by the impacts of climate change in more regions. 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 suggests that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael *et al.*, 2012).

Water scarcity is predicted to increase as a result of climate change in large portions of Africa, South Asia and the Americas (Fung *et al.*, 2011). Modeling by Fung *et al.* (2011) suggests that while population growth will be the primary determinant of water scarcity in a +2°C world, in a +4°C scenario climate change will become the more important driver. It is prudent to assume such climate-induced water scarcity will lead to social and geopolitical tensions that may result in conflict, violence and displacement.

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves with an increases prevalence of enclosed living and working environments, first for their most vulnerable members: the young, old, ill, and manual laborers. Reliance on the needed infrastructure, however, also entails increased vulnerability to unreliability of electricity and water supplies. What once was an inconvenience can become a serious health hazard if many people rely on such protection (Anderson and Bell, 2012).

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 the latter, i.e., measures to mitigate the atmospheric concentration of warming CAPs (climate altering pollutants) that also hold the potential to significantly benefit human health (Haines *et al.*, 2007; Apsimon *et al.*, 2009; Smith and Balakrishnan, 2009; UNEP, 2011; Shindell *et al.*, 2012).The literature on health co-benefits associated with climate change mitigation strategies falls into five categories (Smith *et al.*, 2009; Smith and Balakrishnan, 2009): Those that also (1) Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants; (2) Increase access to reproductive health services; (3) Decrease ruminant meat consumption; (4) Increase active transport from modifications to the built environment; (5) Increase in urban green-space. In addition, there are side effects of mitigation measures, such as geoengineering, for example, that are potentially deleterious for human health, and these are addressed in WGIII, chapter x. In Table 11-4, we summarize what is known about the five categories, and below provide some additional detail for the first two.

[INSERT TABLE 11-4 HERE
Table 11-4: Summary of recent research on co-benefits of climate change mitigation. See text for details on the first two categories.]

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 two major categories: 1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants if the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; in addition, 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, i.e. carbon neutral. This is because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell *et al*., 2008a) 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 sixth to a quarter in China and India, for example (Chafe *et al*., (Submitted)) indicating that reductions in emissions from household sources could yield co-benefits through the outdoor pollution pathway as well.

Another category of air pollution co-benefits comes from controls for methane emissions that both reduce radiative forcing and potentially reduces 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 sulphate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett *et al*., 2009). As noted in Section 11.2, outdoors, the production and distribution of some secondary co-pollutants is exacerbated by temperature-associated attributes of climate change itself, thus posing a positive feedback effect.

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*., forthcoming in 2013).

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, chronic and 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 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, including child pneumonia (Smith *et al*., 2011), blood pressure (McCracken *et al*., 2007; Baumgartner *et al*., 2011), 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 (IPCC, 2007; Ramanathan and Carmichael, 2008; Bond *et al*., 2013). 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). The conclusion is that BC abatement represents an opportunity to achieve both climate mitigation and health benefits, a conclusion shared by other recent reviews as well (UNEP, 2011).

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

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong CAP, methane (CH_4) is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is a CAP. 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 *et al*., 2006) 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, the CRA of 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. (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 (Lefohn *et al.*, 2010). This is consistent with the US EPA (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 (US EPA, 2010; Lefohn *et al.*, 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 particle 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). See also WGI, Ch. x.

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).

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).

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 combined fabric, ventilation, 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 (Markandya *et al.*, 2009). 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 health benefits greatly 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 is another factor involved in the consumption of resources and emissions of CAPs. Although population growth rates and total population size do not alone determine emissions (WG1), 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 aresa such as the Sahel region of Africa with both high fertility and high vulnerabity 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 rich ones like the US, where there is unmet need for services as well as high CO_2 emissions per capita. 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 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 between <19 and <25 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 et al. (Zhu, 2005) found, in a review of three studies performed in the United States that a J-shaped relationship existed between inter-pregnancy spacing in that the lowest risk of adverse birth outcomes (i.e., low birth weight, existed between 18-23 months and risk increased as it departed, in either direction (Zhu, 2005).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing (as preceding birth intervals), malnutrition, and reductions in child, infant and neonatal mortality (Figure 11-8) with risk of child malnutrition 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 (Rutstein, 2005; Gribble *et al*., 2009).

[INSERT FIGURE 11-8 HERE
Figure 11-8: Reduction in child (under 5 years) mortality due to increasing spacing of birth (Previous Birth Interval) based on studies in 17 countries. Source: Rutstein (2005).]

11.9.2.2.Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, which are also the age groups most wishing 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, which can both lead to long term physical and mental developmental problems (Tsui *et al*., 2007). Childbearing at later ages (>35 years) is associated with increased risks for the child of miscarriage, perinatal mortality, preterm birth, low birth weight, congenital and chromosomal abnormalities, and increased risks for the mother of placental previa, gestational diabetes, cesarean delivery and maternal death (Cleary-Goldman *et al*., 2005; Ujah *et al*., 2005).

Thus, 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). 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 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. Conclusions

11.10.1. It is certain that a range of human diseases are sensitive to climate conditions, but the health impacts of these diseases are also affected by many other changing factors, making it currently difficult to quantify precisely the influence of climate change itself on present-day patterns of disease globally.

11.10.2. Much reduction of health impacts from climate change can be avoided through provision of basic health improvements to world’s poor populations.

11.10.3. Much additional reduction can come from targeted adaptation efforts, such as early warning systems and good disaster management.

11.10.4. The world is not progressing rapidly with these advances, however, leading to a likely increasing net health impact from climate change in next decades.

11.10.5. There are residual health impacts that cannot be handled through adaptation in any reasonable way particularly if climate change proceeds to extreme conditions.

11.10.6. Well-chosen adaptation and mitigation measures may achieve substantial health gains (co-benefits), in the short- to medium-term.

11.11. Key Uncertainties and Research Recommendations

The key uncertainty for estimating health impacts from climate change over the next few decades is the extent that society will provide basic public health services, disaster warning and response systems, and poverty alleviation throughout the world. With a strong response, climate change health effects will be relatively small, but otherwise climate-attributable cases of disease and injury will steadily increase. Research is needed into exactly how interventions should be implemented to optimally improve health in the short-term, and lower the health threat of climate change. Another question that warrants attention is the best ways to motivate local, national, and international actions to greatly reduce servere poverty, and improve health services and disaster warning/response systems. More work needs to be done as well to evaluate the effects and costs of health adaptation policies and interventions.

There is a lack of robust analytical methods to untangle complex climate–health relationships such as the effect of more extreme weather on water and sanitation provision and diarrhoea rates (WHO/DFID, 2010). Risk assessment frameworks are needed that not only make the best use of traditional epidemiologic methods but also take into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and the effects on multiple physical and biotic systems that have the potential for diverse and widespread effects, including high-impact events.

In the longer term, there are plausible scenarios for rather extreme climate regimes by the end of the century or before, on pathways that are committed to even more extreme climates in the following century. It is difficult to do research directly on the effect of conditions that do not exist yet at any scale. Nevertheless, trying to understand the health impacts of these lower probability but severe future climates that could potentially affect the lives of nearly every baby born from today onwards given global life expectancies should have high priority. This understanding can help society understand how valuable actions today are to both mitigate and be ready for such conditions.

Frequently Asked Questions

FAQ 11.1: How is climate change thought to affect human health?

There are three major routes by which climate change is thought to affect health 1) by direct impacts, such as heat stress and floods; 2) by indirect impacts mediated through the natural environment, such as shifts in patterns of disease-carrying mosquitoes and waterborne diseases; and 3) indirect impacts mediated through societal systems, such as damage to health care systems by extreme weather events, malnutrition and mental illness from altered agricultural production, and stress and malnutrition from population displacement due to sea-level rise.

FAQ 11.2: Will climate change have benefits for health?

Yes, some populations in temperate areas may be at less risk from extreme cold and some populations may benefit from greater agricultural productivity and lower levels of vector-borne disease, but the overall impact for nearly all populations and for the world as a whole is expected to be much more negative than beneficial.

FAQ 11.3: Who is most affected by climate change?

As climate change mainly acts to exacerbate existing disease patterns and for the next decades will not probably not create significant new ones, those populations already under stress from disease will be most affected. Thus, most assessments indicate that it is poor and disenfranchised groups everywhere that 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, malnutrition, and diarrhea.

FAQ 11.4: What is the most important adaptation strategy to reduce the health impacts of climate change?

Accelerating current public health and medical interventions directed toward reducing existing disease in the world, particularly for climate-related diseases in poor countries, is the single most important step that can be taken to reduce the health impacts of climate change. Reducing poverty is the next most important for health globally.

FAQ 11.5: What are health "co-benefits" of climate change mitigation measures?

A number of mitigation measures to reduce emissions of climate-altering pollutants (CAPs) seem to have important direct health benefits in addition to reducing the risk of climate change, a relationship called "co-benefits." For example, increasing energy efficiency reduces health-damaging air pollution from fuel combustion; reducing ruminant meat consumption in many populations reduces both CAPs and the risk of chronic disease such as cancer; increasing the opportunities and attractiveness of active transport (walking and cycling) in place of travel by motor vehicle reduces air pollution and improves health directly; and providing access to reproductive health services slows population and energy demand growth and reduces risks of child and maternal mortality.

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Table 11-1: Vector-borne diseases.

Disease	Population at risk millions (m) / billions (b)			Climate Sensitivity[1]and Confidence in Climate Effect: increased(>) or decreased (<)temperature(T) rainfall(R) humidity(H); increased cases(+) decreased cases (-)both reported (±); high confidence in global effect - B**old,** high confidence in local effect -*italic*, low confidence in effect - roman	Key References
	Area	Cases^{-yr}	At risk		
Malaria	Mainly Africa, SE Asia,	247m	3.3b	*>T*^{2,3} + - ± *<R* *>R*^{2,3} + - *>H*^{2,3} -	WHO 2008, Kelly-Hope *et* al 2009, Omumbo *et al* 2011, Alonso *et al* 2011.
Dengue	100 countries esp Asia Pacific	50-100m	2.5b	**>T+** **<R-** **<T-** **>H**^{3}**+ -** **>R +**	Beebe 2009, Descloux 2012; Earnest *et al* 2012, Pham *et al* 2011. Kovat et al. 2013
Tick-borne diseases					
T-b encephalitis	Europe, Russian Fed Mongolia China	10,000-12,000		S^{3}	Tokarevich *et al* 2011
Lyme	Temperate areas of Europe, Asia N.America	≤23000 in USA		>T^{3}+ >H^{3}+	Bennet 2006, Ogden *et al* 2008,
Other vector-borne diseases					
Hemorrhagic fever (HFRS)	Global	0.15 – 0.2m		T+ H+ R+	Fang *et al* 2010
Plague	Endemic in natural foci globally			T+ <R^{3}+ >R^{3}+±	Stenseth *et al* 2006, Xu *et al* 2011
Other infectious diseases					
Nosocomial infections	All Hospitals			T+ H+	Perencevich *et al* 2008
Influenza	Global			>T^{3}+ R_^{3} <T^{3}+ >H^{3} +-	Soebiyanto *et al* 2010, Tamerius *et al* 2011
Rotavirus	Global	0.45m		*>T*^{3,4}-,± *>H-* *>R -*	Patel *et al* 2012, Pitzer *et al* 2011
Tuberculosis	Global	1.7m	100-200m	>R^{3} +	Ane-Anyangwe *et al* 2006, Naranbat *et al* 2009;

[1] All diseases included show some seasonality of occurrence

S – no specific climate drivers reported

[2] Effects are *Anopheles* spp

[3] Location specific

[4] Seasonal peaks changed following vaccination

Table 11-2: Projected future health impacts of climate change through air pollution.

Location	Health impact	Models used		Climate scenario	Key assumptions	Outcome	Reference
United States	Ozone-related morbidity and mortality	Multipollutant, multiscale air quality from Community Multiscale Air Quality (CMAQ) Modeling System	GISS-GCM driven by A1B SRES emissions scenario for the period 1950-2055 and downscaled to a 36-km resolution using Mesoscale Meteorological model version 5 (MM5)	Global temperature increase of 1.59°C in 2050, compared to 1990s	Population held constant at 2000 levels	Climate change-driven air quality-related health effects will adversely affect greater than 2/3 of the continental U.S	Potential Impact of Climate Change on Air Pollution-Related Human Health Effects (Tagaris et al. 2009)
	$PM_{2.5}$-related morbidity and mortality	Meteorological data from Goddard Institute for Space Studies (GISS) Global Climate Model (GCM)			Mortality rates held constant at 2000 levels	Approximately 4000 additional annual premature deaths due to climate change impacts on $PM_{2.5}$ compared to 300 due to climate change-induced ozone changes	
		Penn State/NCAR Meso scale Model (MM5 model) used to downscale GISS-GCM outputs to a regional scale			Disease incidence rates held constant at 2000 levels	$PM_{2.5}$ and ozone-related health impacts vary spatially	
		Health effect analysis conducted using U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP)				Increased premature mortality due to elevated ozone concentrations will be offset by lower mortality from reductions in $PM_{2.5}$ in 11 states	
South-central Canada (Montreal, Ottawa, Toronto, Windsor)	air pollution mortality	GCM	GCM downscaled using regression-based statistical method for the periods 2040-2059 and 2070-2089	Air temperature from SRES A2 and B2 scenarios	Population and age structure not directly taken into account	Air pollution-related mortality could increase about 20–30% by the 2050s and 30–45% by the 2080s, projected with climate change	Differential and combined impacts of extreme temperatures and air pollution on human mortality in south-central Canada. Part II: future estimates (Cheng et al. 2008)
						Increase in air pollution-related mortality would be largely driven by increases in ozone effects	
Africa, Middle East, South Asia, Southeast Asia, East Asia, Japan and Australia, Former Soviet Union, Europe, North America, Latin America	Premature ozone-related mortality	GCM	GCM and LMDz-INCA models driven by SRES A2 emissions scenario for 2030	Baseline simulation from 2000	World population of 9.17 billion by 2030	Under current legislation (CLE) scenario, estimated reduction in premature ozone-related human mortalities by 190,000 globally in 2030, mostly in Africa	Human mortality effects of future concentrations of tropospheric ozone (West et al. 2007)
		Laboratoire de Météorologie Dynamique (LMDz)-Interaction Chimie - Aérosols (INCA) chemistry-climate model			Spatial distribution by region based on 2003 population from Landscan database	Under maximum feasible reduction (MFR) scenario, estimated reduction in premature ozone-related human mortalities by 460,000 in 2030, with the greatest reductions in South Asia	
					Constant baseline mortality rates through 2030		

Table 11-3: Number of malnourished children less than 5 years of age (in millions) in 2000 and under the NCAR climate model (using A2 scenario from AR4) till 2050. Assumptions for investment in agricultural productivity: + only in developing countries; ++ both in developing and developed countries. Results assume no CO_2 fertilization effects. Adapted from (Nelson *et al.*, 2009).

Scenario	South Asia	East Asia/ Pacific	Eu + Centr. Asia	LA & Carrib.	Middle East/ N.Africa	Sub2-Sah. Africa	Devel. Countr.
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
NCAR	59.1	14.5	3.7	6.4	2.1	52.2	138.5
NCAR + adaptation	54.2	10.1	3.0	4.9	1.4	44.1	118.9
NCAR ++adaptat'n	53.7	10.5	3.0	4.8	1.3	43.5	117.2

Table 11-4: Summary of recent research on co-benefits of climate change mitigation. See text for details on the first two categories.

Co-benefit category	**Benefits for health**	**Benefits for climate**	**Select publications since 2006**
Reduction of co-pollutants from outdoor and household sources	See text	See text	(Bell *et al*., 2008a)
			(Markandya, Armstrong et al. 2009)
			(Smith and Balakrishnan, 2009)
			(Smith, Jerrett et al. 2009)
			(Wilkinson *et al*., 2009)
			(Lefohn, Shadwick et al. 2010)
			(World Health Organization Regional Office for Europe 2010)
			(Po *et al*., 2011)
			(Anenberg *et al*., 2012)
			(Lim, Vos et al. 2012)
Greater access to reproductive health services	See text	See text	(Conde-Agudelo *et al*., 2007)
			(Tsui, Creanga et al. 2007)
			(Gribble, Murray et al. 2009)
			(Prata 2009)
			(O'Neill, Jackman et al. 2010)
			(Diamond-Smith, Potts 2011)
			(Potts and Henderson, 2012)
Increases in urban green space	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status	Reduce air pollution; more carbon sequestration (through forests and soil)	(McMichael, Powles et al. 2007)
			(Mitchell and Popham, 2007)
			(Babey *et al*., 2008)
			(Friel, Dangour et al. 2009)
			(Maas *et al*., 2009)
			(van den Berg *et al*., 2010)
			(van Dillen *et al*., 2011)
Less ruminant (red) meat consumption	May reduce (ischaemic) heart disease, stroke, colorectal cancer, breast cancer and prevalence of overweight/obese individuals	Fewer CH_4 emissions	(Sinha, Cross et al. 2009)
			(Smith and Balakrishnan, 2009)
			(Jakszyn *et al*., 2011)
			(Pan, Sun et al. 2012)
			(Xu *et al*., 2012)
Increases in active transport from modifications to the built environment, including smart growth	Increased physical activity; reduced obesity; reduced chronic disease; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety	Reduce CAP emissions associated with vehicle transport; possible mitigation of emissions through sequestration	(Babey *et al*., 2007)
			(Reed and Ainsworth, 2007)
			(Kaczynski and Henderson, 2008)
			(Casagrande *et al*., 2009)
			(Rundle *et al*., 2009)
			(Woodcock *et al*., 2009)
			(Grabow *et al*., 2011)
			(Durand *et al*., 2011)
			(McCormack and Shiell, 2011)

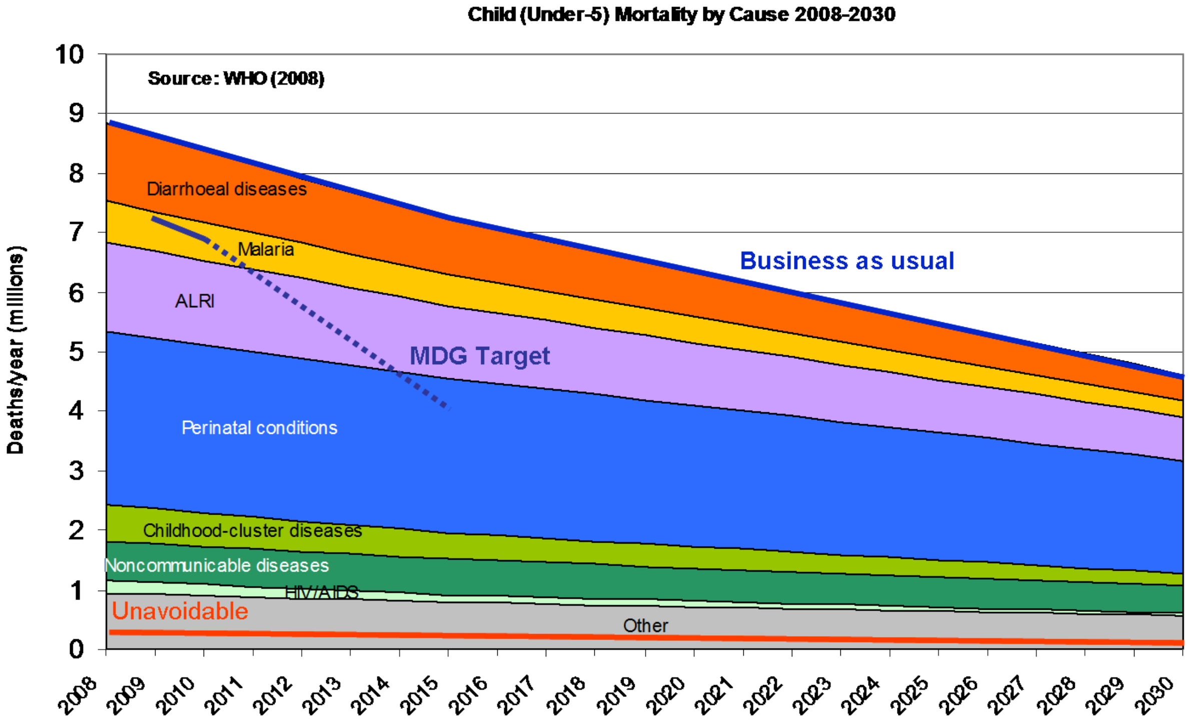


Figure 11-1: Climate change acts against human development: to reach the Millennium Development Goal for child mortality, the reduction in climate-sensitive causes of death at an early age must accelerate. Projected Child Mortality, 2008-2030, Including Climate-Sensitive Causes. ALRI is Acute Lower Respiratory Infections. Sources: Mortality projections by cause from WHO. Population projections from UN DESA. Child mortality rates from IGME. (Interagency Group for Child Mortality Estimation, 2011; United Nations, Department of Economic and Social Affairs, Population Division., 2011; World Health Organization, 2008).

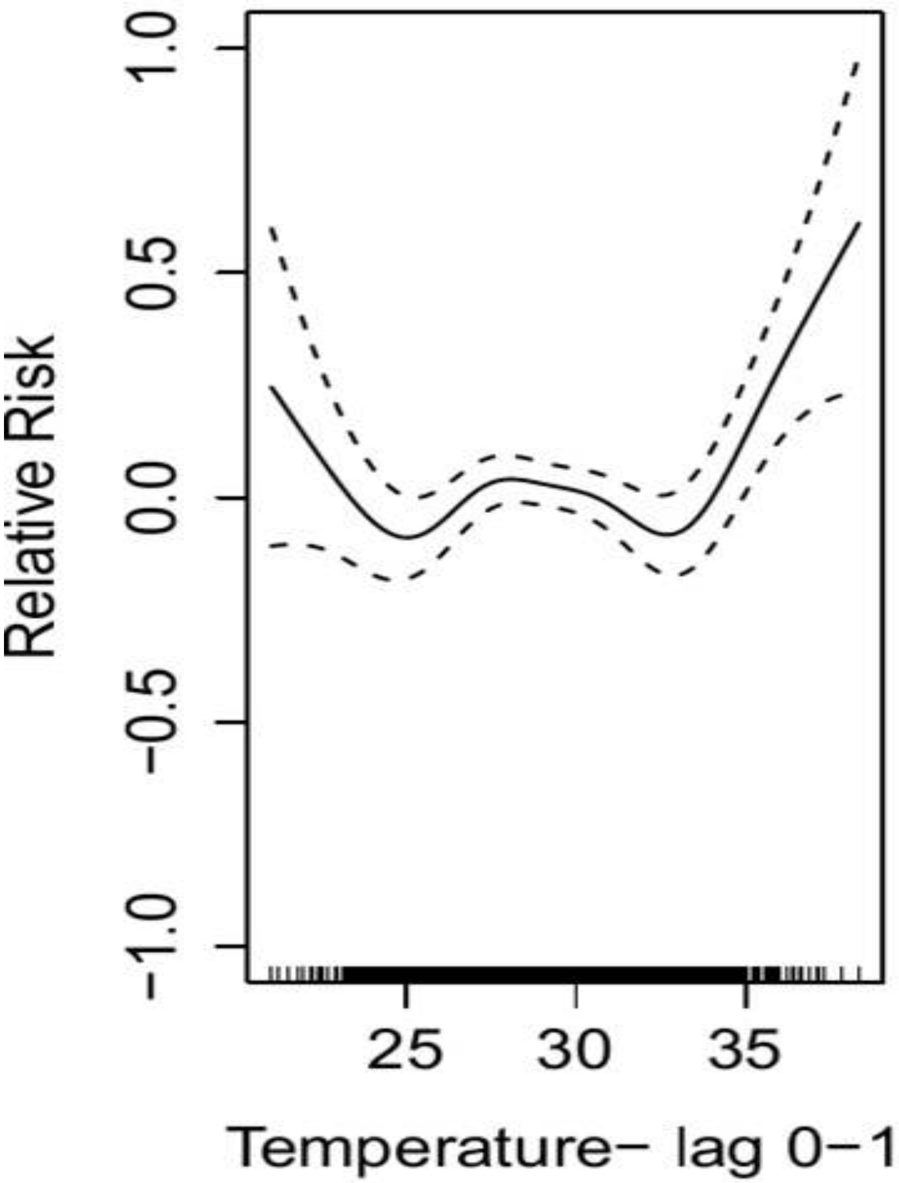
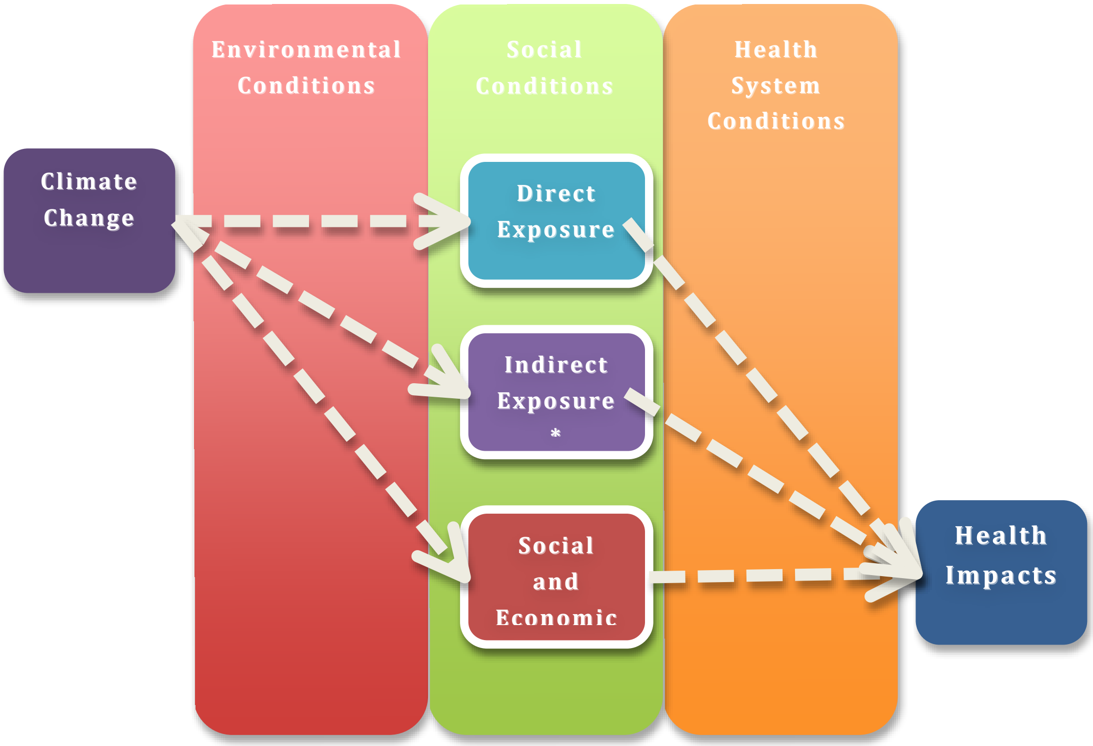


Figure 11-2: Relationship between the risk of dying and average temperature on the preceding day, persons aged over 60 years, Nouna, Burkina Faso. Y-axis: log(RR), X-axis: Temp in °C, lagged by one day. Dotted lines show 95% confidence limits. Source: Diboulo et al, 2012.



*Changes in water, air, food quality; vector ecology; ecosystems, agriculture, industry, and settlements
†Arrow inside 'condition' box indicates modifying influence

Figure 11-3: Ways in which climate, climate variability and climate change may influence human health. Source: E. Garcia (2011).

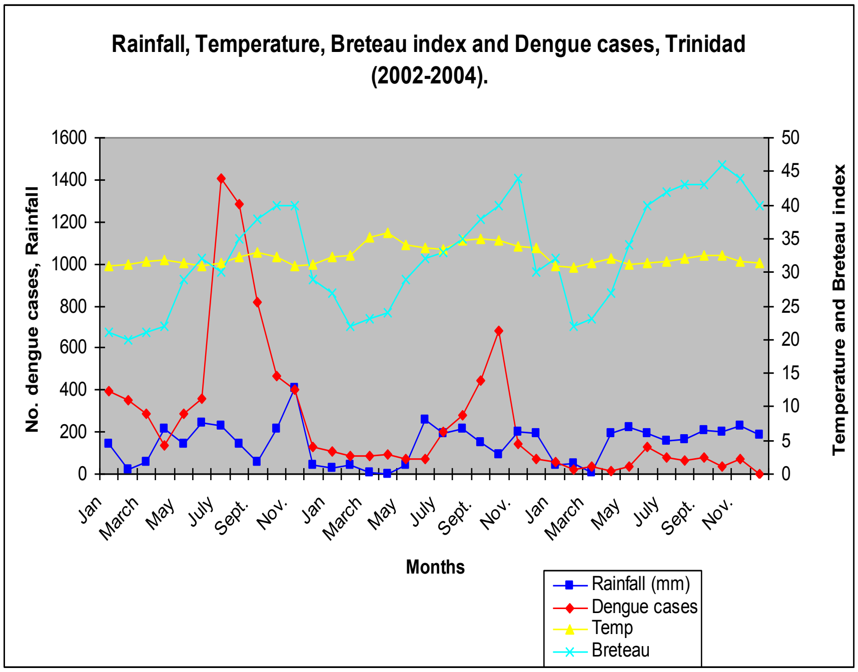


Figure 11-4: Rainfall, temperature, Breteau index (number of water containers with *A. aegypti* larvae per 100 houses), and dengue cases, Trinidad (2002-2004). Source: Chadee *et al.* (2007).

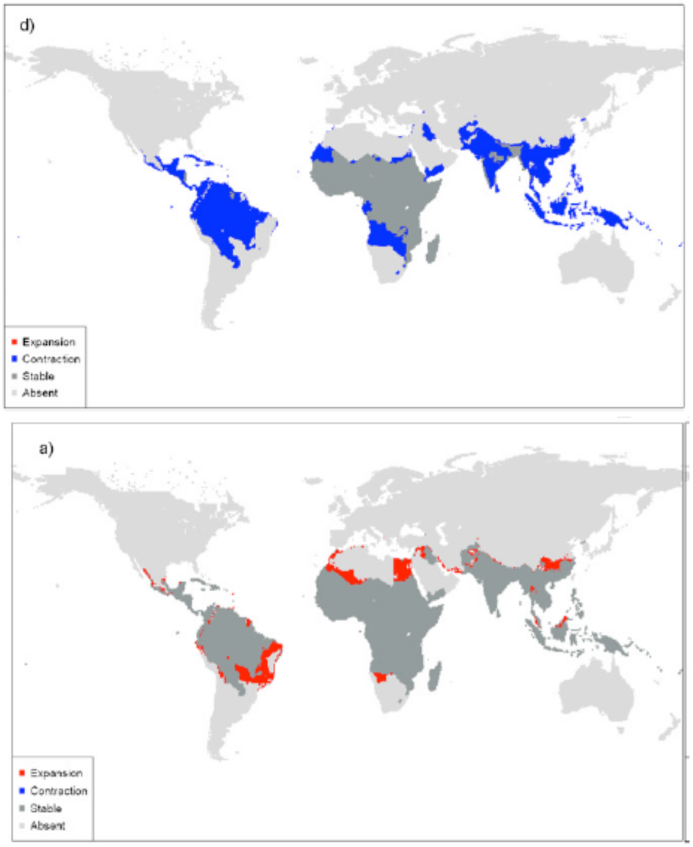


Figure 11-5: Contraction of the area of malaria transmission if economic development progresses as forecast (top panel, in blue); expansion in areas of transmission through higher temperatures (bottom panel, in red). Based on IPCC scenario A1B, projections to 2050. Source: Béguin *et al*. (2011).

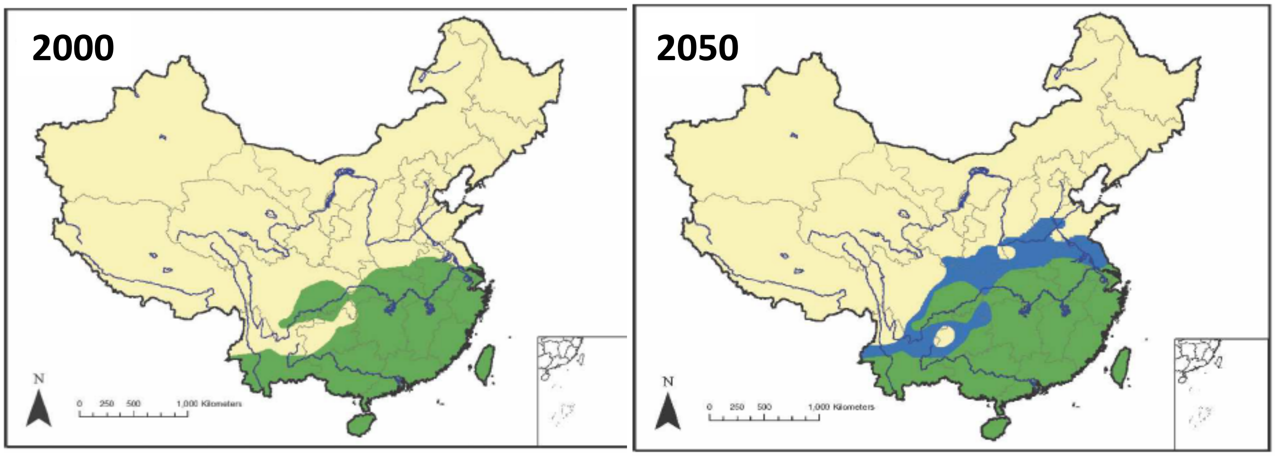


Figure 11-6: Projected risk map of schistosomiasis*(S. japonicum)* transmission in China in 2050. For comparison the current risk map in 2000. Green area denotes the range of schistosomiasis in 2000. The blue area shows the geographic expansion. Adapted from (Zhou *et al*., 2008).

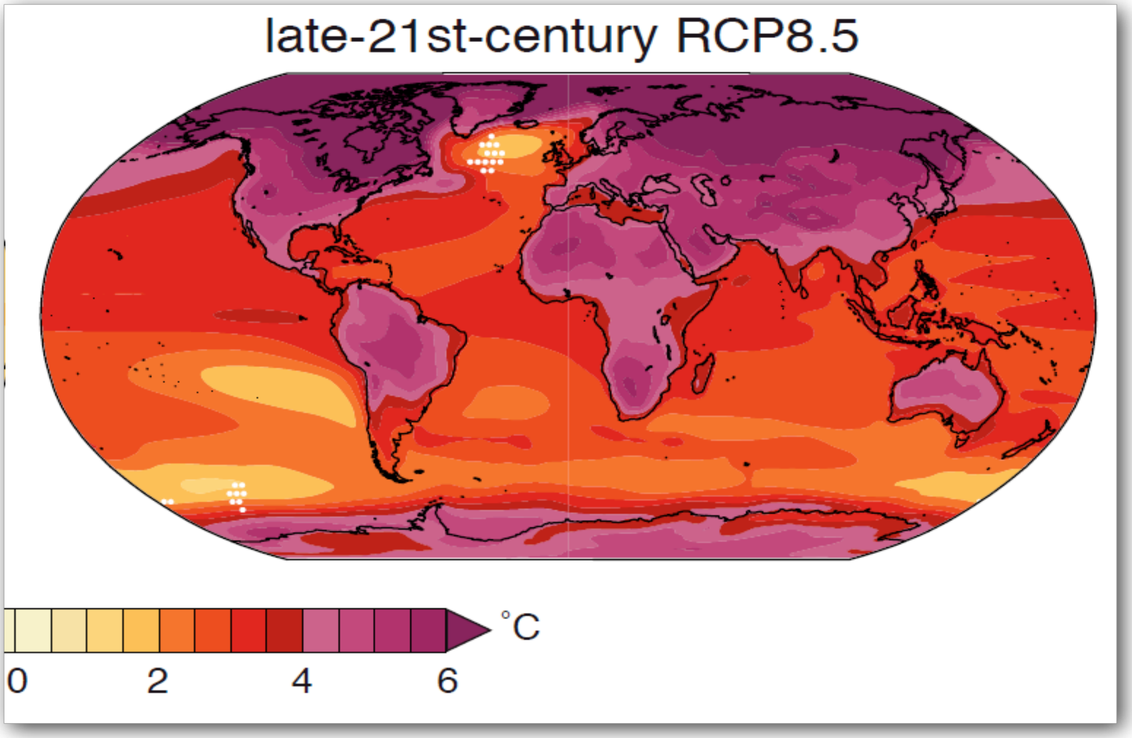


Figure 11-7: Extreme warming by 2100 from RCP8.5. Mean temperatures above levels around 2000. Note higher effects over land. Source: WGI AR5 _____.

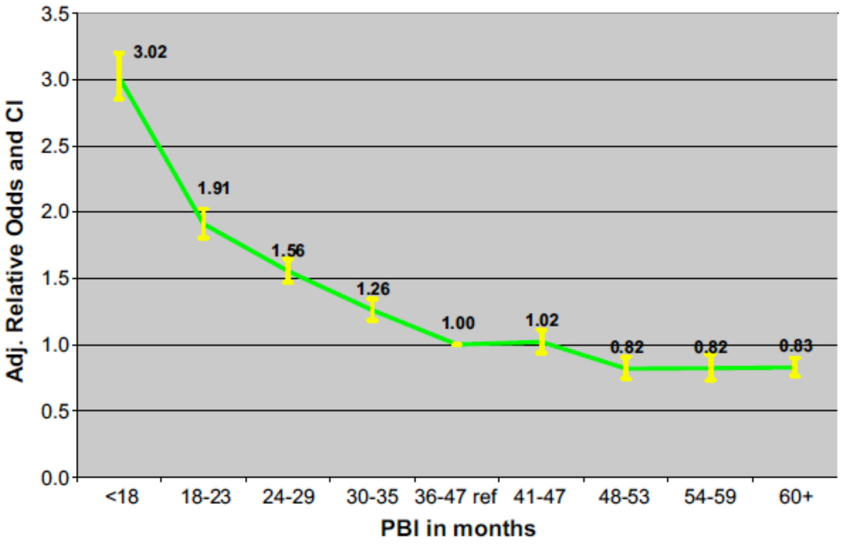


Figure 11-8: Reduction in child (under 5 years) mortality due to increasing spacing of birth (Previous Birth Interval) based on studies in 17 countries. Source: Rutstein (2005).