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Human Health

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EXECUTIVE SUMMARY

Global climate change will have a wide range of health impacts. Overall, negative health impacts are anticipated to outweigh positive health impacts. Some health impacts would result from changes in the frequencies and intensities of extremes of heat and cold and of floods and droughts. Other health impacts would result from the impacts of climate change on ecological and social systems and would include changes in infectious disease occurrence, local food production and nutritional adequacy, and concentrations of local air pollutants and aeroallergens, as well as various health consequences of population displacement and economic disruption.

There is little published evidence that changes in population health status actually have occurred as yet in response to observed trends in climate over recent decades. A recurring difficulty in identifying such impacts is that the causation of most human health disorders is multifactorial and the "background" socioeconomic, demographic, and environmental context varies constantly. A further difficulty is foreseeing all of the likely types of future health effects, especially because for many of the anticipated future health impacts it may be inappropriate to extrapolate existing risk-function estimates to climatic-environmental conditions not previously encountered. Estimation of future health impacts also must take account of differences in vulnerability between populations and within populations over time.

Research since the Second Assessment Report (SAR) mainly has described the effect of climate variability, particularly daily and seasonal extremes, on health outcomes. Studies of health impacts associated with the El Niño-Southern Oscillation (ENSO) have identified interannual climate-health relationships for some epidemic diseases. The upward trend in worldwide numbers of people adversely affected by weather disasters has been characterized by peak impacts during El Niño events. Meanwhile, there has been an expanded effort to develop, test, and apply mathematical models for predicting various health outcomes in relation to climate scenarios. This mix of epidemiological studies and predictive modeling leads to the following conclusions.

An increase in the frequency or intensity of heat waves will increase the risk of mortality and morbidity, principally in older age groups and the urban poor (high confidence). The greatest increases in thermal stress are forecast for higher latitude (temperate) cities, especially in populations that have limited resources, such as access to air conditioning. The pattern of acclimatization to future climate regimes is difficult to estimate. Recent modeling of heat wave impacts in U.S. urban populations, allowing for acclimatization, suggests that several U.S. cities would experience, on average, several hundred extra deaths per summer. Poor urban populations in developing countries may be particularly vulnerable to the impacts of increased heat waves, but no equivalent predictions are available. Warmer winters and fewer cold spells, because of climate change, will decrease cold-related mortality in many temperate countries (high confidence). The reduction in winter deaths will vary between populations. Limited evidence indicates that, in at least some temperate countries, reduced winter deaths would outnumber increased summer deaths.

Any regional increases in climate extremes (storms, floods, cyclones, etc.) associated with climate change would cause physical damage, population displacement, and adverse effects on food production, freshwater availability and quality, and would increase the risks of infectious disease epidemics, particularly in developing countries (very high confidence/ well-established). Over recent years, several major climate-related disasters have had major adverse effects on human health—including floods in China, Mozambique, Bangladesh, and Europe; famine in Sudan; and Hurricane Mitch, which devastated Central America. Although these events cannot be confidently attributed to climate change, they indicate the susceptibility of vulnerable populations to the adverse effects of such events.

Climate change will cause some deterioration in air quality in many large urban areas, assuming that current emission levels continue (medium to high confidence). Increases in exposure to ozone and other air pollutants (e.g., radon, forest fire particulates) could increase known morbidity and mortality effects.

Vector-borne diseases are maintained in complex transmission cycles involving blood-feeding arthropod vectors (and usually reservoir hosts) that depend on specific ecological conditions for survival. These diseases are sensitive to climatic conditions, although response patterns vary between diseases. In areas with limited or deteriorating public health infrastructure, and where temperatures now or in the future are permissive of disease transmission, an increase in temperatures (along with adequate rainfall) will cause certain vector-borne diseases (including malaria, dengue, and leishmaniasis) to extend to higher altitudes (medium to high confidence) and higher latitudes (medium to low confidence). Higher temperatures, in combination with conducive patterns of rainfall and surface water, will prolong transmission seasons in some endemic locations (medium to high confidence). In other locations, climate change will decrease transmission via reductions in rainfall or temperatures that are too high for transmission (low to medium confidence). In all such situations, the actual health impacts of changes in potential infectious disease transmission will be strongly determined by the effectiveness of the public health system.

Mathematical models indicate that climate change scenarios over the coming century would modestly increase the proportion of world population living in regions of potential transmission of malaria and dengue (medium to high confidence). These models are limited by their reliance on climate factors, without reference to modulating influences of environmental, ecological, demographic, or socioeconomic factors. Although the most recent of several biologically based model studies suggests that the increase in population living in regions of potential malaria transmission would be on the order of an extra 260–320 million people in 2080 (against a baseline expectation of about 8 billion), a recent statistically based modeling study, which incorporated conservative assumptions, estimated that there would be no net change in actual transmission of malaria by 2080, assuming a business-as-usual climate scenario and adaptation. In the latter study, regional increases and decreases would approximately cancel out.

Changes in climate, including changes in climate variability, would affect many other vector-borne infections (such as various types of mosquito-borne encephalitis, Lyme disease, and tick-borne encephalitis) at the margins of current distributions (medium to high confidence). For some diseases—such as malaria in the Sahel, Western equine encephalitis in North America, and tick-borne encephalitis in Europe—a net decrease may occur. Changes in surface water quantity and quality will affect the incidence of diarrheal diseases (medium confidence). Ocean warming will facilitate transmission of cholera in coastal areas (low confidence; speculative).

Fish and shellfish poisoning is closely associated with marine ecology. There is some evidence that sea-surface warming associated with El Niño increases the risk to humans of ciguatera poisoning and the occurrence of toxic (and ecologically harmful) algal blooms. Climate change will increase the incidence of ciguatera poisoning and shellfish poisoning (low confidence).

Climate change represents an additional pressure on the world's food supply system and is expected to increase yields at higher latitudes and lead to decreases at lower latitudes. These regional differences in climate impacts on agricultural yield are likely to grow stronger over time, with net beneficial effects on yields and production in the developed world and net negative effects in the developing world. This would increase the number of undernourished people in the developing world (medium confidence).

In some settings, the impacts of climate change may cause social disruption, economic decline, and displacement of populations. The ability of affected communities to adapt to such disruptive events will depend on the social, political, and economic situation of the country and its population. The health impacts associated with such social-economic dislocation and population displacement are substantial [high confidence; well-established].

For each anticipated adverse health impact there is a range of social, institutional, technological, and behavioral adaptation options to lessen that impact. There is a basic and general need for public health infrastructure (programs, services, surveillance systems) to be strengthened and maintained. It also is crucial for nonhealth policy sectors to appreciate how the social and physical conditions of living affect population health.

Our scientific capacity to model the various potential health outcomes of climate change is limited. Nevertheless, it is clear that for many health outcomes—especially for those that result indirectly from a sequence of environmental and social impacts—precise and localized projections cannot yet be made. In the meantime, a precautionary approach requires that policy development proceed on the basis of available—though often limited and qualitative—evidence of how climate change will affect patterns of human population health. Furthermore, high priority should be assigned to improving the public health infrastructure and developing and implementing effective adaptation measures.

9.1. Introduction and Scope

This chapter assesses how climatic changes and associated environmental and social changes are likely to affect human population health. Such an assessment necessarily takes account of the multivariate and interactive ecological framework within which population health and disease are determined. This *ecological* perspective recognizes that the foundations of long-term good health lie in the continued stability and functioning of the biosphere's natural systems—often referred to as "life-support systems."

Deliberate modification of these ecological and physical systems by human societies throughout history has conferred many social, economic, and public health benefits. However, it also has often created new risks to health, such as via mobilization of infectious agents, depletion of freshwater supplies, and reduced productivity of agroecosystems (Hunter *et al*., 1993; Gubler, 1996). Consider, for example, the chain of consequences from clearance of tropical forests. In the first instance, it typically leads to a warmer and drier local climate. The consequent drying of soil and loss of its organic structure predisposes the area to increased water runoff during heavy rainfall. This, in turn, can endanger human health via flooding, water contamination, impaired crop yields, and altered patterns of vector-borne infectious diseases. Meanwhile, forest clearance also contributes to the atmospheric buildup of carbon dioxide (CO_2) and hence to climate change and its health impacts.

Today, as the scale of human impact on the environment increases, a range of population health impacts can be expected from these large-scale changes in the Earth's life-support systems (Watson *et al.*, 1998). That is the complex context within which actual and potential health impacts of global climate change must be assessed.

9.1.1. Summary of IPCC Second Assessment Report (1996): Potential Health Impacts of Climate Change

The IPCC Second Assessment Report (McMichael *et al*., 1996a) relied on the relatively limited scientific literature that had emerged during the late 1980s and early 1990s. Most published studies were on health impacts associated with climate variability (e.g., El Niño) and extreme events (natural disasters and heat waves). Predictive modeling of future health impacts was in an early developmental stage.

The SAR noted the many inherent uncertainties in forecasting the potential health impacts of climate change. This included recognition that various other changes in social, economic, demographic, technological, and health care circumstances would unfold over coming decades and that these developments would "condition" the impact of climatic and environmental changes on human health. However, such accompanying changes can be foreseen neither in detail nor far into the future.

The overall assessment was that the likely health impacts would be predominantly adverse. Reflecting the published literature, most of the specific assessments were nonquantitative and relied on expert judgment. They drew on reasoned extrapolations from knowledge of health hazards posed by extreme weather events, increases in temperature-dependent air pollution, summertime increases in certain types of food poisoning, and the spectrum of public health consequences associated with economic disruption and physical displacement of populations. It was noted that the projected effects of climate change on agricultural, animal, and fishery productivity could increase the prevalence of malnutrition and hunger in food-insecure regions experiencing productivity downturns.

For two of the anticipated health impacts, the published literature available by 1995 allowed a more quantitative approach. The relevant conclusions were as follows:

- An increase in the frequency or severity of heat waves would cause a short-term increase in (predominantly cardiorespiratory) deaths and illness. In some very large cities (e.g., Atlanta, Shanghai) by about 2050, this would result in up to several thousand extra heat-related deaths annually. This heat-related mortality increase would be offset by fewer cold-related deaths in milder winters, albeit to an extent that was not yet adequately estimated and likely to vary between populations.
- Climate-induced changes in the geographic distribution and biological behavior of vector organisms of vector-borne infectious diseases (e.g., malaria-transmitting mosquitoes) and infective parasites would alter—usually increase—the potential transmission of such diseases. For example, simulations with global/regional mathematical models indicated that, in the absence of demographic shifts, the proportion of the world's population living within the potential malaria transmission zone would increase from ~45% in the 1990s to ~60% by 2050. Some localized decreases in malaria transmissibility also may occur in response to climate change.

9.1.2. Population Health and its Significance as an Outcome of Climate Change

This is the last of the sector-impact chapters in this volume. This is appropriate because human population health is influenced by an extensive "upstream" range of environmental and social conditions. Indeed, over time, the level of health in a population reflects the quality of social and natural environments, material standards of living, and the robustness of the public health and health service infrastructure. Therefore, population health is an important integrating index of the effects of climate change on ecosystems, biological processes, physical environmental media, and the social-economic environment.

Two other points are important. First, the causation of most human diseases is complex and multifactorial. Second, there is great heterogeneity in the types of disease: acute and chronic;

infectious and noninfectious; physical injury and mental health disorders. These two considerations explain some of the difficulties in fully understanding and quantifying the influences of climate on human health.

Profiles of health and disease vary greatly between regions and countries and over time. Currently, noncommunicable diseases (including mental health disorders) predominate in developed countries, with cardiovascular diseases and cancer accounting for more than half of all deaths. In poorer countries, infectious diseases (especially in childhood) remain important, even as noncommunicable diseases increase in urbanizing populations that are exposed to changes in lifestyle and environmental and occupational exposures. Globally, infectious diseases remain a major cause of human morbidity and are responsible for approximately one-third of all deaths (WHO, 1999a). Many of these water-, food-, and vector-borne infectious diseases are sensitive to climate.

9.2. Research into the Relationship between Climate Change and Health: Caveats and Challenges

9.2.1. New Knowledge about Climate Change Impacts on Health

Since the SAR, much of the additional research on health impacts has examined natural climate variability in relation to interannual variations in infectious diseases—particularly vector-borne diseases—and the relationship between daily weather and mortality in various urban populations. Predictive modeling of the impact of climate scenarios on vector-borne disease transmissibility has undergone further development. Meanwhile, however, data sets that allow study of the effects of the health impacts of observed longer term trends in climate remain sparse.

9.2.2. Characteristics and Methodological Difficulties

The research task of assessing the actual and potential health impacts of climate change has several distinctive characteristics and poses four major challenges to scientists:

1) Anticipated anthropogenic climate change will be a gradual and long-term process. This projected change in mean climate conditions is likely to be accompanied by regional changes in the frequency of extreme events. Changes in particular health outcomes already may be occurring or soon may begin to occur, in response to recent and ongoing changes in world climate. Identification of such health effects will require carefully planned epidemiological studies.
2) In epidemiological studies (in which associations are observed with or without knowledge of likely causal mechanisms), there often are difficulties in estimating the role of climate *per se* as a cause of change in health status. Changes in climate typically are accompanied by various other environmental changes. Because most diseases have multiple contributory causes, it often is difficult to attribute causation between climatic factors and other coexistent factors. For example, in a particular place, clearing of forest for agriculture and extension of irrigation may coincide with a rise in regional temperature. Because all three factors could affect mosquito abundance, it is difficult to apportion between them the causation of any observed subsequent increase in mosquito-borne infection. This difficulty is well recognized by epidemiologists as the "confounding" of effects.
3) It is equally important to recognize that certain factors can modify the vulnerability of a particular population to the health impacts of climate change or variability. This type of effect-modification (or "interaction") can be induced by endogenous characteristics of the population (such as nutritional or immune status) or contextual circumstances that influence the "sensitivity" of the population's response to the climate change (such as unplanned urbanization, crowding, or access to air conditioning during heat waves). Deliberate social, technological, or behavioral adaptations to reduce the health impacts of climate change are an important category of effect-modifying factor.
4) Simulation of scenario-based health risks with predictive models entails three challenges. These challenges relate to validity, uncertainty, and contextual realism:
   - Valid representation of the main environmental and biological relationships and the interacting ecological and social processes that influence the impact of those relationships on health is difficult. A balance must be attained between complexity and simplicity.
   - There are various sources of (largely unavoidable) uncertainty. There is uncertainty attached to the input scenarios of climate change (and of associated social, demographic, and economic trends). Subsequently, there are three main types of uncertainties in the modeling process itself: "normal" statistical variation (reflecting stochastic processes of the real world); uncertainty about the correct or appropriate values of key parameters in the model; and incomplete knowledge about the structural relationships represented in the model.
   - Climate change is not the sole global environmental change that affects human health. Various large-scale environmental changes now impinge on human population health simultaneously, and often interactively (Watson *et al.*, 1998). An obvious example is vector-borne infectious diseases, which are affected by climatic conditions, population movement, forest clearance and land-use patterns, freshwater surface configurations, human population density, and the population density of insectivorous predators (Gubler, 1998b). In accordance with point 2 above, each change in health outcome must be appropriately apportioned between climate and other influences.

9.3. Sensitivity, Vulnerability, and Adaptation

There are uncertainties regarding the sensitivity (i.e., rate of change of the outcome variable per unit change in the input/exposure variable) of many health outcomes to climate or climate-induced environmental changes. Relatively little quantitative research, with estimation of exposure-response relationships, has been done for outcomes other than death rates associated with thermal stress and changes in the transmission potential of several vector-borne infectious diseases. There has been increased effort to map the current distribution of vectors and diseases such as malaria by using climate and other environmental data (including satellite data).

Continuation of recent climatic trends soon may result in some shifts in the geographic range and seasonality of diseases such as malaria and dengue. In reality, however, such shifts also would depend on local topographical and ecological circumstances, other determinants of local population vulnerability, and the existence and level of adaptive public health defenses. There has been some recent debate in the scientific literature about whether there is any evidence of such shifts yet (Epstein *et al.*, 1997; Mouchet *et al.*, 1998; Reiter, 1998a,b). It is not yet clear what criteria are most appropriate for assessment of climatic influences on such changes in infectious disease patterns. A balance is needed between formal, statistically based analysis of changes within a particular local setting and a more synthesizing assessment of the consistency of patterns across diverse settings and across different systems—physical, biotic, social, and public health. As with climate change itself, there is an inherent difficulty in detecting small climate-induced shifts in population health outcomes and in attributing the shift to a change in climate.

Population vulnerability is a function of the extent to which a health outcome in that particular environmental-demographic setting is sensitive to climate change and the capacity of the population to adapt to new climate conditions. Determinants of population vulnerability to climate-related threats to health include level of material resources, effectiveness of governance and civil institutions, quality of public health infrastructure, access to relevant local information on extreme weather threats, and preexisting burden of disease (Woodward *et al.*, 1998). Thus, vulnerability is determined by individual, community, and geographical factors:

- *Individual factors include:*
  - Disease status (people with preexisting cardiovascular disease, for example, may be more vulnerable to direct effects such as heat waves)
  - Socioeconomic factors (in general, the poor are more vulnerable)
  - Demographic factors (the elderly are more vulnerable to heat waves, for example, and infants are more vulnerable to diarrheal diseases).
- *Community factors may include:*
  - Integrity of water and sanitation systems and their capacity to resist extreme events
  - Local food supplies and distribution systems
  - Access to information, including early warnings of extreme climate events
  - Local disease vector distribution and control programs.
- *Geographical factors may include:*
  - The influence of El Niño cycle or the occurrence of extreme weather events that are more common in some parts of the world
  - Low-lying coastal populations more vulnerable to the effects of sea-level rise
  - Populations bordering current distributions of vector-borne disease particularly vulnerable to changes in distribution
  - Rural residents often with less access to adequate health care, and urban residents more vulnerable to air pollution and heat island effects
  - Environmentally degraded and deforested areas more vulnerable to extreme weather events.

Understanding a population's capacity to adapt to new climate conditions is crucial to realistic assessment of the potential health impacts of climate change (Smithers and Smit, 1997). This issue is addressed more fully in Section 9.11.

9.4. Thermal Stress (Heat Waves, Cold Spells)

9.4.1. Heat Waves

Global climate change is likely to be accompanied by an increase in the frequency and intensity of heat waves, as well as warmer summers and milder winters (see Table 3-10). The impact of extreme summer heat on human health may be exacerbated by increases in humidity (Gaffen and Ross, 1998; Gawith *et al.*, 1999).

Daily numbers of deaths increase during very hot weather in temperate regions (Kunst *et al.*, 1993; Ando, 1998a,b). For example, in 1995, a heat wave in Chicago caused 514 heat-related deaths (12 per 100,000 population) (Whitman *et al.*, 1997), and a heat wave in London caused a 15% increase in all-cause mortality (Rooney *et al.*, 1998). Excess mortality during heat waves is greatest in the elderly and people with preexisting illness (Sartor *et al.*, 1995; Semenza *et al.*, 1996; Kilbourne, 1997; Ando *et al.*, 1998a,b). Much of this excess mortality from heat waves is related to cardiovascular, cerebrovascular, and respiratory disease. The mortality impact of a heat wave is uncertain in terms of the amount of life lost; a proportion of deaths occur in susceptible persons who were likely to have died in the near future. Nevertheless, there is a high level of certainty that an increase in the frequency and intensity of heat waves would increase the numbers of additional deaths from hot weather. Heat waves also are associated with nonfatal impacts such as heat stroke and heat exhaustion (Faunt *et al.*, 1995; Semenza *et al.*, 1999).

Heat waves have a much bigger health impact in cities than in surrounding suburban and rural areas (Kilbourne, 1997; Rooney *et al.*, 1998). Urban areas typically experience higher—and nocturnally sustained—temperatures because of the "heat island" effect (Oke, 1987; Quattrochi *et al.*, 2000). Air pollution also is typically higher in urban areas, and elevated pollution levels often accompany heat waves (Piver *et al.*, 1999) (see also Section 9.6.1.2 and Chapter 8).

The threshold temperature for increases in heat-related mortality depends on the local climate and is higher in warmer locations. A study based on data from several European regions suggests that regions with hotter summers do not have significantly different annual heat-related mortality compared to cold regions (Keatinge *et al.*, 2000). However, in the United States, cities with colder climates are more sensitive to hot weather (Chestnut *et al.*, 1998). Populations will acclimatize to warmer climates via a range of behavioral, physiological, and technological adaptations. Acclimatization will reduce the impacts of future increases in heat waves, but it is not known to what extent. Initial physiological acclimatization to hot environments can occur over a few days, but complete acclimatization may take several years (Zeisberger *et al.*, 1994).

Weather-health studies have used a variety of derived indices—for example, the air mass-based synoptic approach (Kalkstein and Tan, 1995) and perceived temperature (Jendritzky *et al.*, 2000). Kalkstein and Greene (1997) estimated future excess mortality under climate change in U.S. cities. Excess summer mortality attributable to climate change, assuming acclimatization, was estimated to be 500–1,000 for New York and 100–250 for Detroit by 2050, for example. Because this is an isolated study, based on a particular method of treating meteorological conditions, the chapter team assigned a medium level of certainty to this result.

The impact of climate change on mortality from thermal stress in developing country cities may be significant. Populations in developing countries (e.g., in Mexico City, New Delhi, Jakarta) may be especially vulnerable because they lack the resources to adapt to heat waves. However, most of the published research refers to urban populations in developed countries; there has been relatively little research in other populations.

9.4.2. Decreased Mortality Resulting from Milder Winters

In many temperate countries, there is clear seasonal variation in mortality (Sakamoto-Momiyama, 1977; Khaw, 1995; Laake and Sverre, 1996); death rates during the winter season are 10–25% higher than those in the summer. Several studies indicate that decreases in winter mortality may be greater than increases in summer mortality under climate change (Langford and Bentham, 1995; Martens, 1997; Guest *et al.*, 1999). One study estimates a decrease in annual cold-related deaths of 20,000 in the UK by the 2050s (a reduction of 25%) (Donaldson *et al.*, 2001). However, one study estimates that increases in heat-related deaths will be greater than decreases in cold-related death in the United States by a factor of three (Kalkstein and Greene, 1997).

Annual outbreaks of winter diseases such as influenza, which have a large effect on winter mortality rates, are not strongly associated with monthly winter temperatures (Langford and Bentham, 1995). Social and behavioral adaptations to cold play an important role in preventing winter deaths in high-latitude countries (Donaldson *et al.*, 1998). Sensitivity to cold weather (i.e., the percentage increase in mortality per 1ºC change) is greater in warmer regions (e.g., Athens, southern United States) than in colder regions (e.g., south Finland, northern United States) (Eurowinter Group, 1997). One possible reason for this difference may be failure to wear suitable winter clothing. In North America, an increase in mortality is associated with snowfall and blizzards (Glass and Zack, 1979; Spitalnic *et al.*, 1996; Gorjanc *et al.*, 1999) and severe ice storms (Munich Re, 1999).

The extent of winter-associated mortality that is directly attributable to stressful weather therefore is difficult to determine and currently is being debated in the literature. Limited evidence indicates that, in at least some temperate countries, reduced winter deaths would outnumber increased summer deaths. The net impact on mortality rates will vary between populations. The implications of climate change for nonfatal outcomes is not clear because there is very little literature relating cold weather to health outcomes.

9.5. Extreme Events and Weather Disasters

Major impacts of climate change on human health are likely to occur via changes in the magnitude and frequency of extreme events (see Table 3-10), which trigger a natural disaster or emergency. In developed countries, emergency preparedness has decreased the total number of tropical cyclone-related deaths (see Section 7.2.2). However, in developed countries, studies indicate an increasing trend in the number and impacts (deaths, injuries, economic losses) of all types of natural disasters (IFRC, 1998; Munich Re, 1999). Some of the interannual variability in rates of persons affected by disasters may be associated with El Niño (Bouma *et al.*, 1997a). The average annual number of people killed by natural disasters between 1972 and 1996 was about 123,000. By far the largest number of people affected (i.e., in need of shelter or medical care) are in Asia, and one study reveals that Africa suffers 60% of all disaster-related deaths (Loretti and Tegegn, 1996).

Populations in developing countries are much more affected by extreme events. Relative to low socioeconomic conditions, the impact of weather-related disasters in poor countries may be 20–30 times larger than in industrialized countries. For example, floods and drought associated with the El Niño event of 1982–1983 led to losses of about 10% in gross national product (GNP) in countries such as Bolivia, Chile, Ecuador, and Peru (50% of their annual public revenue) (Jovel, 1989).

Disasters occur when climate hazards and population vulnerability converge. Factors that affect vulnerability to disasters are shown in Figure 9-1. The increase in population vulnerability

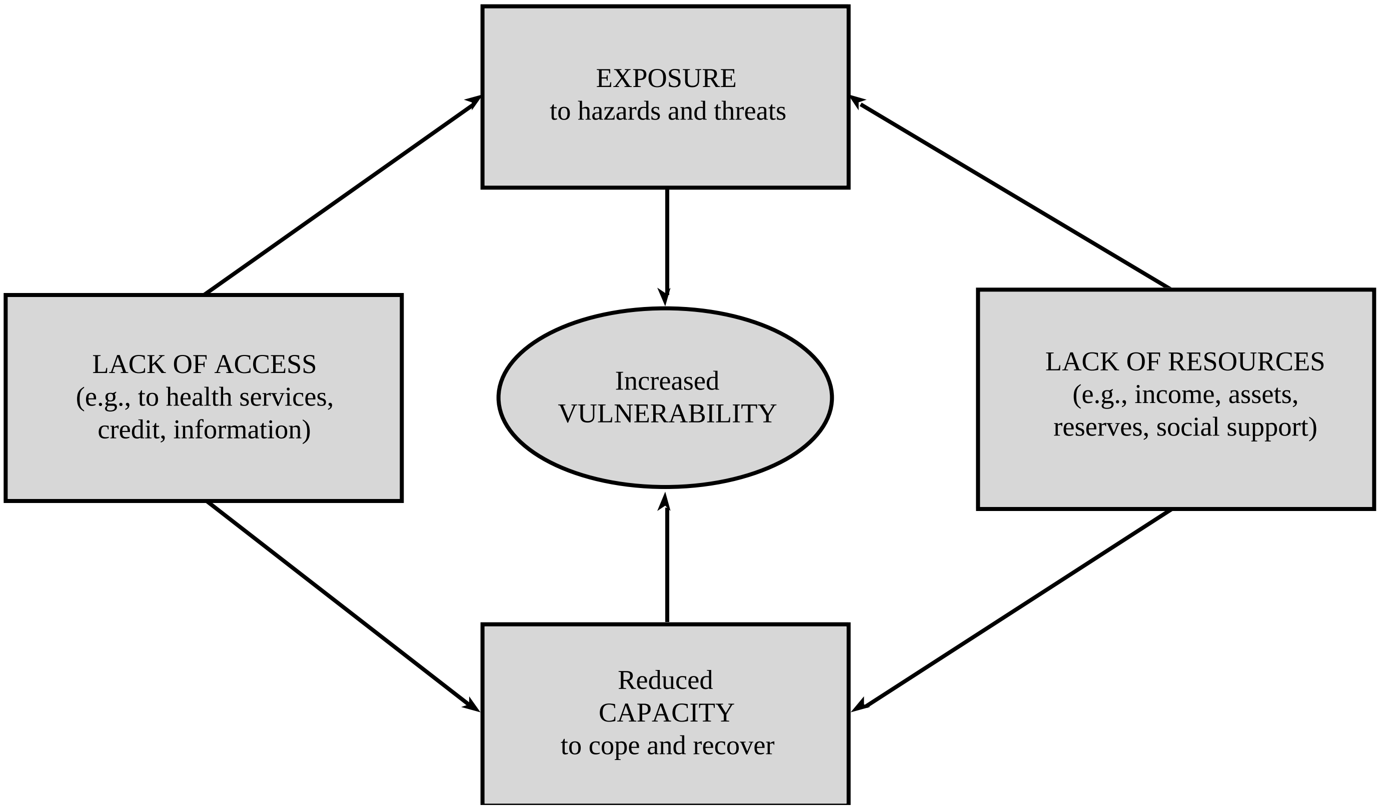

Figure 9-1: Diagrammatic illustration of vulnerability to disasters (McMichael *et al*., 1996b).

to extreme weather is primarily caused by the combination of population growth, poverty, and environmental degradation (Alexander, 1993). Concentration of people and property in high-risk areas (e.g., floodplains and coastal zones) also has increased. Degradation of the local environment also may contribute to vulnerability (see Chapter 7).

The health impacts of natural disasters include (Noji, 1997):

- Physical injury
- Decreases in nutritional status, especially in children
- Increases in respiratory and diarrheal diseases resulting from crowding of survivors, often with limited shelter and access to potable water
- Impacts on mental health, which in some cases may be long-lasting
- Increased risk of water-related diseases as a result of disruption of water supply or sewage systems
- Release and dissemination of dangerous chemicals from storage sites and waste disposal sites into floodwaters.

Extreme weather events cause death and injury directly. However, substantial indirect health impacts also occur because of damage to the local infrastructure and population displacement (see also Section 9.10). Following disasters, fatalities and injuries can occur as residents return to clean up damage and debris (Philen *et al*., 1992). Bereavement, property loss, and social disruption may increase the risk of depression and mental health problems (WHO, 1992). For example, cases of post-traumatic stress disorder were reported in the United States up to 2 years after Hurricane Andrew (Norris *et al.*, 1999).

9.5.1. Floods

Floods are associated with particular dangers to human populations (Menne *et al*., 1999). Climate change may increase the risk of river and coastal flooding (see Chapters 4 and 6). The health impacts of floods may be divided into the immediate, medium, and long terms. Immediate effects are largely death and injuries caused by drowning and being swept against hard objects. Medium-term effects include increases in communicable diseases such as those caused by ingestion of contaminated water (e.g., cholera, hepatitis A), contact with contaminated water (e.g., leptospirosis—see Section 9.7.9.1), or respiratory diseases resulting from overcrowding in shelters. A study in populations displaced by catastrophic floods in Bangladesh in 1988 found that diarrhea was the most common illness, followed by respiratory infection. Watery diarrhea was the most common cause of death for all age groups under 45 (Siddique *et al*., 1991). In rural Bangladesh and Khartoum, Sudan, the proportion of severely malnourished children increased after flooding (Woodruff *et al*., 1990; Choudhury and Bhuiya, 1993). Also, in the aftermath of flooding, molds and fungi may grow on interior surfaces, providing a potent stimulus to allergic persons (American Academy of Pediatrics, 1998).

In China, floods experienced over the past few years have been particularly severe. In 1996, official national statistics showed

200 million people affected by flooding: There were more than 3,000 deaths, and 363,800 people were injured; 3.7 million houses were destroyed, and 18 million houses were damaged. Direct economic loses exceeded US$12 billion (IFRC 1997). In 1998, official national statistics showed 200 million people affected by flooding, more than 3,000 deaths, and 4 million houses damaged; direct economic losses exceeded US$20 billion (National Climate Centre of China, 1998). Nevertheless, the vulnerability of the Chinese population has been reduced by a combination of better preparedness, including sophisticated warning systems, and relief efforts. In the longer term, reforestation may reduce the risk of flooding in these regions.

In developed countries, physical and disease risks from flooding are greatly reduced by a well-maintained flood control and sanitation infrastructure and public health measures, such as monitoring and surveillance activities to detect and control outbreaks of infectious disease. However, the experience of the central European floods of 1997, when more than 100 people died, showed that even in industrialized countries floods can have a major impact on health and welfare. In Poland, 6,000 km^2 were flooded, and 160,000 people were evacuated from their homes. The cost of the damage was estimated at US$3 billion [2.7% of 1996 gross domestic product (GDP)]. In the Czech Republic, 50,000 people were evacuated and damage was estimated at US$1.8 billion (3.7% of GDP) (IFRC, 1998). There was an increase in cases of leptospirosis in the Czech Republic (Kriz *et al.*, 1998). Floods also have an important impact on mental health in the affected community (WHO, 1992; Menne *et al.*, 1999). Increases in suicide, alcoholism, and psychological and behavioral disorders, particularly among children, were reported following floods in Poland in 1997 (IFRC 1998).

9.5.2. Storms and Tropical Cyclones

Impoverished and high-density populations in low-lying and environmentally degraded areas are particularly vulnerable to tropical cyclones (also called hurricanes and typhoons). Many of the most serious impacts of tropical cyclones in the 20th century have occurred in Bangladesh because of the combination of meteorological and topographical conditions, along with the inherent vulnerability of this low-income, poorly resourced population. Tropical cyclones also can cause landslides and flooding. Most deaths are caused by drowning in the storm surge (Alexander, 1993; Noji, 1997). The impacts of cyclones in Japan and other developed countries have been decreasing in recent years because of improved early warning systems. However, the experience of Hurricane Mitch demonstrated the destructive power of an extreme event on a densely populated and poorly resourced region (PAHO, 1999).

9.5.3. Droughts

The health impacts of drought on populations occur primarily via impacts on food production. Famine often occurs when a preexisting situation of malnutrition worsens. The health consequences of drought include diseases resulting from malnutrition (McMichael *et al.*, 1996b). In times of shortage, water is used for cooking rather than hygiene. In particular, this increases the risk of diarrheal diseases (as a result of fecal contamination) and water-washed diseases (e.g., trachoma, scabies). Outbreaks of malaria can occur during droughts as a result of changes in vector breeding sites (Bouma and van der Kaay, 1996). Malnutrition also increases susceptibility to infection.

In addition to adverse environmental conditions, political, environmental, or economic crises can trigger a collapse in food marketing systems. These factors may have a cumulative or synergistic effect. For example, a breakdown in the reserve food supply system resulting from the sale of grain or livestock reserves might be exacerbated by conflict and breakdown in law and order. The major food emergency in Sudan during 1998 illustrates the interrelationship between climatic triggers of famine and conflict. Land mines made portions of major roads in southern Sudan impassable and contributed to poor access for relief supplies. By July 1998, the World Food Programme's air cargo capacity had increased to more than 10,000 t to overcome the transport difficulties. These air cargoes were supplemented by barge convoys and road repair projects (WFP, 1999). Vulnerability to drought and food shortages can be greatly reduced through the use of seasonal forecasts as part of an early warning system (see Section 9.11.1).

9.6. Air Pollution

9.6.1. Gases, Fine Particulates

Weather conditions influence air pollution via pollutant (or pollutant precursor) transport and/or formation. Weather conditions also can influence biogenic (e.g., pollen production) and anthropogenic (e.g., as a result of increased energy demand) air pollutant emissions. Exposure to air pollutants can have many serious health effects, especially following severe pollution episodes. Studies that are relevant to climate change and air pollution can be divided into two categories: those that estimate the combined impact of weather and air pollutants on health outcomes and those that estimate future air pollution levels. Climate change may increase the concentration of ground-level ozone, but the magnitude of the effect is uncertain (Patz *et al.*, 2000). For other pollutants, the effects of climate change and/or weather are less well studied.

Current air pollution problems are greatest in developing country cities. For example, nearly 40,000 people die prematurely every year in India because of outdoor air pollution (World Bank, 1997). Air quality also is one of the main concerns for environmental health in developed countries (Bertollini *et al.*, 1996; COMEAP, 1998).

Radon is an inert radioactive gas. The rate at which it is emitted from the ground is sensitive to temperature (United Nations, 1982). High indoor exposures are associated with an increased risk of lung cancer (IARC, 1988). There is some evidence from modeling experiments that climate warming may increase radon concentrations in the lower atmosphere (Cuculeanu and Iorgulescu, 1994).

9.6.1.1. Effects of Air Pollution, Season, and Weather on Health

The six standard air pollutants that have been extensively studied in urban populations are sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), lead, and particulates. The impact of some air pollutants on health is more evident during the summer or during high temperatures (Bates and Sizto, 1987; Bates *et al.*, 1990; Castellsague *et al.*, 1995; Bobak and Roberts, 1997; Katsouyanni *et al.*, 1997; Spix *et al.*, 1998; de Diego Damia *et al.*, 1999; Hajat *et al.*, 1999).For example, the relationship between SO_2 and total and cardiovascular mortality in Valencia (Ballester *et al.*, 1996) and Barcelona, Spain (Sunyer *et al.*, 1996), and Rome, Italy (Michelozzi *et al.*, 1998), was found to be stronger during hot periods than during winter. However, Moolgavkar *et al.* (1995) conclude that, in Philadelphia, SO_2 had the strongest health effects in spring, autumn, and winter. Increases in daily mortality and morbidity (indicated by hospital admissions) are associated with high ozone levels on hot days in many cities (e.g., Moolgavkar *et al.*, 1995; Sunyer *et al.*, 1996; Touloumi *et al.*, 1997).

High temperatures also have acute effects on mortality (see Section 9.4.1). Some studies have found evidence of an interaction between the effects of ozone and the effects of higher temperatures (e.g., Katsouyanni *et al.*, 1993; Sartor *et al.*, 1995). Other studies addressing the combined effects of weather and particulate air pollution have not found evidence of such an interaction (e.g., Samet *et al.*, 1998). Correlations between climate and site-specific air quality variables must be further evaluated and, in some instances, need to include temperature, pollution, and interaction terms in regression models.

Climate change is expected to increase the risk of forest and rangeland fires (see Section 5.6.2.2.1). Haze-type air pollution therefore is a potential impact of climate change on health. Majors fires in 1997 in southeast Asia and the Americas were associated with increases in respiratory and eye symptoms (Brauer, 1999; WHO, 1999b). In Malaysia, a two- to three-fold increase in outpatient visits for respiratory disease and a 14% decrease in lung function in school children were reported. In Alta Floresta, Brazil, there was a 20-fold increase in outpatient visits for respiratory disease. In 1998, fires in Florida were linked to significant increases in emergency department visits for asthma (91%), bronchitis (132%), and chest pain (37%) (CDC, 1999). However, a study of 1994 bushfires in western Sydney showed no increase in asthma admissions to emergency departments (Smith *et al.*, 1996).

9.6.1.2. Future Changes in Air Quality

Weather has a major influence on the dispersal and ambient concentrations of air pollutants. Large high-pressure systems often create an inversion of the normal temperature profile, trapping pollutants in the shallow boundary layer at the Earth's surface. It is difficult to predict the impact of climate change on local urban climatology and, therefore, on average local air pollution concentrations. However, any increase in anticyclonic conditions in summer would tend to increase air pollution concentrations in cities (Hulme and Jenkins, 1998).

Box 9-1. Stratospheric Ozone Depletion and Exposure to Ultraviolet Radiation

Stratospheric ozone destruction is an essentially separate process from greenhouse gas (GHG) accumulation in the lower atmosphere. However, not only are several of the anthropogenic GHGs [e.g., chlorofluorocarbons (CFCs) and N_2O] also ozone-depleting gases but tropospheric warming apparently induces stratospheric cooling, which exacerbates ozone destruction (Shindell *et al.*, 1998; Kirk-Davidoff *et al.*, 1999). Stratospheric ozone shields the Earth's surface from incoming solar ultraviolet radiation (UVR), which has harmful effects on human health. Long-term decreases in summertime ozone over New Zealand have been associated with significant increases in ground-level UVR, particularly in the DNA-damaging waveband (McKenzie *et al.*, 1999). In a warmer world, patterns of personal exposure to solar radiation (e.g., sunbathing in temperate climates) also are likely to change.

Many epidemiological studies have implicated solar radiation as a cause of skin cancer (melanoma and other types) in fair-skinned humans (IARC, 1992; WHO, 1994). The most recent assessment by UNEP (1998) projects significant increases in skin cancer incidence as a result of stratospheric ozone depletion. High-intensity UVR also damages the eye's outer tissue, causing "snowblindness"—the ocular equivalent of sunburn. Chronic exposure to UVR is linked to conditions such as pterygium (WHO, 1994). The role of UV-B in cataract formation is complex. Some cataract subtypes appear to be associated with UVR exposure, whereas others do not. In humans and experimental animals, UVR can cause local and whole-body immunosuppression (UNEP, 1998). Cellular immunity has been shown to be affected by ambient doses of UVR (Garssen *et al.*, 1998). Concern exists that UVR-induced immunosuppression could influence patterns of infectious disease. Nevertheless, no direct evidence exists for such effects in humans, and uncertainties remain about the underlying biological processes.

Formation and destruction of ozone is accelerated by increases in temperature and ultraviolet radiation. Existing air quality models have been used to examine the effect of climate change on ozone concentrations (e.g., Morris *et al.*, 1989; Penner *et al.*, 1989; Morris *et al.*, 1995; Sillman and Samson, 1995). The models indicate that decreases in stratospheric ozone and elevated temperature increase ground-level ozone concentration. An increase in occurrence of hot days could increase biogenic and anthropogenic emissions of volatile organic compounds (e.g., from increased evaporative emissions from fuel-injected automobiles) (Sillman and Samson, 1995). These studies of the impact of climate change on air quality must be considered indicative but by no means definitive. Important local weather factors may not be adequately represented in these models.

9.6.2. Aeroallergens (e.g., Pollen)

Daily, seasonal, and interannual variation in the abundance of many aeroallergens, particularly pollen, is associated with meteorological factors (Emberlin, 1994, 1997; Spieksma *et al.*, 1995; Celenza *et al.*, 1996). The start of the grass pollen season can vary between years by several weeks according to the weather in the spring and early summer. Pollen abundance, however, is more strongly associated with land-use change and farming practices than with weather (Emberlin, 1994). Pollen counts from birch trees (the main cause of seasonal allergies in northern Europe) have been shown to increase with increasing seasonal temperatures (Emberlin, 1997; Ahlholm *et al.*, 1998). In a study of Japanese cedar pollen, there also was a significant increase in total pollen count in years in which summer temperatures had risen (Takahashi *et al.*, 1996). However, the relationship between meteorological variables and specific pollen counts can vary from year to year (Glassheim *et al.*, 1995). Climate change may affect the length of the allergy season. In addition, the effect of higher ambient levels of CO_2 may affect pollen production. Experimental research has shown that a doubling in CO_2 levels, from about 300 to 600 ppm, induces an approximately four-fold increase in the production of ragweed pollen (Ziska and Caulfield, 2000a,b).

High pollen levels have been associated with acute asthma epidemics, often in combination with thunderstorms (Hajat *et al.*, 1997; Newson *et al.*, 1998). Studies show that the effects of weather and aeroallergens on asthma symptoms are small (Epton *et al.*, 1997). Other assessments have found no evidence that the effects of air pollutants and airborne pollens interact to exacerbate asthma (Guntzel *et al.*, 1996; Stieb *et al.*, 1996; Anderson *et al.*, 1998; Hajat *et al.*, 1999). Airborne pollen allergen can exist in subpollen sizes; therefore, specific pollen/asthma relationships may not be the best approach to assessing the risk (Beggs, 1998). One study in Mexico suggests that altitude may affect the development of asthma (Vargas *et al.*, 1999). Sources of indoor allergens that are climate-sensitive include the house dust mite, molds, and cockroaches (Beggs and Curson, 1995). Because the causation of initiation and exacerbation of asthma is complex, it is not clear how climate change would affect this disease. Further research into general allergies (including seasonal and geographic distribution) is required.

9.7. Infectious Diseases

The ecology and transmission dynamics of infectious diseases are complex and, in at least some respects, unique for each disease within each locality. Some infectious diseases spread directly from person to person; others depend on transmission via an intermediate "vector" organism (e.g., mosquito, flea, tick), and some also may infect other species (especially mammals and birds).

The "zoonotic" infectious diseases cycle naturally in animal populations. Transmission to humans occurs when humans encroach on the cycle or when there is environmental disruption, including ecological and meteorological factors. Various rodent-borne diseases, for example, are dependent on environmental conditions and food availability that determine rodent population size and behavior. An explosion in the mouse population following extreme rainfall from the 1991–1992 El Niño event is believed to have contributed to the first recorded outbreak of hantavirus pulmonary syndrome in the United States (Engelthaler *et al.*, 1999; Glass *et al.*, 2000).

Many important infectious diseases, especially in tropical countries, are transmitted by vector organisms that do not regulate their internal temperatures and therefore are sensitive to external temperature and humidity (see Table 9-1). Climate change may alter the distribution of vector species—increasing or decreasing the ranges, depending on whether conditions are favorable or unfavorable for their breeding places (e.g., vegetation, host, or water availability). Temperature also can influence the reproduction and maturation rate of the infective agent within the vector organism, as well as the survival rate of the vector organism, thereby further influencing disease transmission.

Changes in climate that will affect potential transmission of infectious diseases include temperature, humidity, altered rainfall, and sea-level rise. It is an essential but complex task to determine how these factors will affect the risk of vector- and rodent-borne diseases. Factors that are responsible for determining the incidence and geographical distribution of vector-borne diseases are complex and involve many demographic and societal—as well as climatic—factors (Gubler, 1998b). An increase in vector abundance or distribution does not automatically cause an increase in disease incidence, and an increase in incidence does not result in an equal increase in mortality (Chan *et al.*, 1999). Transmission requires that the reservoir host, a competent arthropod vector, and the pathogen be present in an area at the same time and in adequate numbers to maintain transmission. Transmission of human diseases is dependent on many complex and interacting factors, including human population density, housing type and location, availability of screens and air conditioning on habitations, human behavior, availability of reliable piped water, sewage and waste management systems, land use and irrigation systems, availability and efficiency of vector control programs, and general environmental hygiene. If all of these factors are favorable for transmission, several meteorological factors may influence the intensity of transmission (e.g., temperature, relative humidity, and precipitation patterns). All of the foregoing factors influence the transmission dynamics of a disease and play a role in determining whether endemic or epidemic transmission occurs.

The resurgence of infectious diseases in the past few decades, including vector-borne diseases, has resulted primarily from demographic and societal factors—for example, population growth, urbanization, changes in land use and agricultural practices, deforestation, international travel, commerce, human and animal movement, microbial adaptation and change, and breakdown in public health infrastructure (Lederberg *et al*., 1992; Gubler, 1989, 1998a). To date, there is little evidence that climate change has played a significant role in the recent resurgence of infectious diseases.

The following subsections describe diseases that have been identified as most sensitive to changes in climate. The majority of these assessments rely on expert judgment. Where models have been developed to assess the impact of climate change, these also are discussed.

9.7.1. Malaria

Malaria is one of the world's most serious and complex public health problems. The disease is caused by four distinct species of plasmodium parasite, transmitted between individuals by Anopheline mosquitoes. Each year, it causes an estimated 400–500 million cases and more than 1 million deaths, mostly

Table 9-1*: Main vector-borne diseases: populations at risk and burden of disease (WHO data).*

Disease	Vector	Population at Risk	Number of People Currently Infected or New Cases per Year	Disability-Adjusted Life Years Lost[a]	Present Distribution
Malaria	Mosquito	2400 million (40% world population)	272,925,000	39,300,000	Tropics/subtropics
Schistosomiasis	Water Snail	500–600 million	120 million	1,700,000	Tropics/subtropics
Lymphatic filariasis	Mosquito	1,000 million	120 million	4,700,000	Tropics/subtropics
African trypanosomiasis (sleeping sickness)	Tsetse Fly	55 million	300,000–500,000 cases yr^{-1}	1,200,000	Tropical Africa
Leishmaniasis	Sandfly	350 million	1.5–2 million new cases yr^{-1}	1,700,000	Asia/Africa/ southern Europe/ Americas
Onchocerciasis (river blindness)	Black Fly	120 million	18 million	1,100,000	Africa/Latin America/ Yemen
American trypanosomiasis (Chagas'disease)	Triatomine Bug	100 million	16–18 million	600,000	Central and South America
Dengue	Mosquito	3,000 million	Tens of millions cases yr^{-1}	1,800,000[b]	All tropical countries
Yellow fever	Mosquito	468 million in Africa	200,000 cases yr^{-1}	Not available	Tropical South America and Africa
Japanese encephalitis	Mosquito	300 million	50,000 cases yr^{-1}	500,000	Asia

[a] Disability-Adjusted Life Year (DALY) = a measurement of population health deficit that combines chronic illness or disability and premature death (see Murray, 1994; Murray and Lopez, 1996). Numbers are rounded to nearest 100,000.
[b] Data from Gubler and Metzer (1999).

Table 9-2: *Effect of climate factors on vector- and rodent-borne disease transmission.*

Climate Factor	Vector	Pathogen	Vertebrate Host and Rodents
Increased temperature	– Decreased survival, e.g., *Culex. tarsalis* (Reeves *et al*., 1994) – Change in susceptibility to some pathogens (Grimstad and Haramis, 1984; Reisen, 1995); seasonal effects (Hardy *et al*., 1990) – Increased population growth (Reisen, 1995) – Increased feeding rate to combat dehydration, therefore increased vector–human contact – Expanded distribution seasonally and spatially	– Increased rate of extrinsic incubation in vector (Kramer *et al*., 1983; Watts *et al*., 1987) – Extended transmission season (Reisen *et al*., 1993, 1995) – Expanded distribution (Hess *et al*., 1963)	– Warmer winters favor rodent survival
Decreases in precipitation	– Increase in container-breeding mosquitoes because of increased water storage – Increased abundance for vectors that breed in dried-up river beds (Wijesunder, 1988) – Prolonged droughts could reduce or eliminate snail populations	– No effect	– Decreased food availability can reduce populations – Rodents may be more likely to move into housing areas, increasing human contact
Increases in precipitation	– Increased rain increases quality and quantity of larval habitat and vector population size – Excess rain can eliminate habitat by flooding – Increased humidity increases vector survival – Persistent flooding may increase potential snail habitats downstream	– Little evidence of direct effects – Some data on humidity effect on malarial parasite development in *Anopheline* mosquito host	– Increased food availability and population size (Mills *et al*., 1999)
Increase in precipitation extremes	– Heavy rainfall events can synchronize vector host-seeking and virus transmission (Day and Curtis, 1989) – Heavy rainfall can wash away breeding sites	– No effect	– Risk of contamination of flood waters/runoff with pathogens from rodents or their excrement (e.g., *Leptospira* from rat urine)
Sea-level rise	– Coastal flooding affects vector abundance for mosquitoes that breed in brackish water (e.g., *An. subpictus* and *An. sundaicus* malaria vectors in Asia)	– No effect	– No effect

in children (WHO, 1998a). Malaria is undergoing a global resurgence because of a variety of factors, including complacency and policy changes that led to reduced funding for malaria control programs in the 1970s and 1980s, the emergence of insecticide and drug resistance, human population growth and movement, land-use change, and deteriorating public health infrastructure (Lindsay and Birley, 1996). Variation in malaria transmission also is associated with changes in temperature, rainfall, and humidity as well as the level of immunity (Lindsay and Birley, 1996). All of these factors can interact to affect adult mosquito densities and the development of the parasite within the mosquito (see Table 9-2).

Very high temperatures are lethal to the mosquito and the parasite. In areas where mean annual temperature is close to the physiological tolerance limit of the parasite, a small temperature increase would be lethal to the parasite, and malaria transmission would therefore decrease. However, at low temperatures, a small increase in temperature can greatly increase the risk of malaria transmission (Bradley, 1993; Lindsay and Birley, 1996).

Micro- and macroenvironmental changes can affect malaria transmission. For example, deforestation may elevate local temperatures (Hamilton, 1989). Changes in types of housing may change indoor temperatures where some vectors spend most of the time resting (Garnham, 1945). In Africa, deforestation, vegetation clearance, and irrigation can all provide the open sunlit pools that are preferred by important malaria vectors and thus increase transmission (Chandler and Highton, 1975;

Walsh *et al.*, 1993; Githeko *et al.*, 1996; Lindsay and Birley, 1996).

Malaria currently is present in 101 countries and territories (WHO, 1998a). An estimated 40% (i.e., 2.4 billion people) of the total world population currently lives in areas with malaria. In many malaria-free countries with a developed public health infrastructure, the risk of sustained malaria transmission after reintroduction is low in the near term. Other areas may become at risk as a result of climate change if, for example, malaria control programs have broken down or if transmission currently is limited mainly by temperature. Environmental conditions already are so favorable for malaria transmission in tropical African countries that climate change is unlikely to affect overall mortality and morbidity rates in endemic lowland regions (MARA, 1998). Furthermore, reductions in rainfall around the Sahel may decrease transmission in this region of Africa (Mouchet *et al.*, 1996; Martens *et al.*, 1999). Future climate change may increase transmission in some highland regions, such as in East Africa (Lindsay and Martens, 1998, Mouchet *et al.*, 1998; Cox *et al.*, 1999; see Box 9-2). Studies that map malaria in Africa indicate that, at the broad scale, distribution of the disease is determined by climate, except at the southern limit (MARA, 1998). Malaria transmission currently is well within the climatic limits of its distribution in mid- to high-latitude developed countries because of effective control measures and other environmental changes. However, in South America the southern limits of malaria distribution may be affected by climate change. The southern geographical distribution limit of a major malaria vector in South America (*An. darlingi*) coincides with the April mean isotherm of 20°C. If temperature and rainfall increase in Argentina, *An. darlingi* may extend its distribution in southern Argentina, whereas if rainfall decreases, conditions may become unfavorable for *An. darlingi* (Carcavallo and Curto de Casas, 1996).

Malaria was successfully eradicated from Australia, Europe, and the United States in the 1950s and 1960s, but the vectors were not eliminated (Bruce-Chwatt and de Zulueta, 1980; Zucker, 1996). In regions where the vectors persist in sufficient abundance, there is a risk of locally transmitted malaria. This small risk of very localized outbreaks may increase under climate change. Conditions currently exist for malaria transmission in those countries during the summer months, but few nonimported cases have been reported (Holvoet *et al.*, 1983; Zucker, 1996; Baldari *et al.*, 1998; Walker, 1998). Malaria could become established again under the prolonged pressures of climatic and other environmental-demographic changes if a strong public health infrastructure is not maintained. A particular concern is the reintroduction of malaria in countries of the former Soviet Union with economies in transition, where public health infrastructure has diminished (e.g., Azerbaijan, Russia).

9.7.1.1 Modeling the Impact of Climate Change on Malaria

Classical epidemiological models of infectious disease use the basic reproduction rate, R_0. This measure is defined as the

Box 9-2. Have Recent Increases in Highland Malaria been Caused by Climate Warming?

"Highland malaria" usually is defined as malaria that occurs around its altitudinal limit, exhibiting an unstable fluctuating pattern. There has been considerable debate about the causes of the resurgence of malaria in the African highlands. Early in the 20th century, malaria epidemics occurred at elevations of 1,500–2,500 m in Africa, South America, and New Guinea (Mouchet *et al.,* 1998; Reiter, 1998a). Highland malaria in Africa was effectively controlled in the 1950s and 1960s, mainly through the use of DDT and improved medical care. Important changes that have contributed to the subsequent resurgence include changes in land use, decreasing resources for malaria control and treatment, and population growth and movement (Lindsay and Martens, 1998; Malakooti *et al.*, 1998; Mouchet *et al.*, 1998; Reiter, 1998a). There are insufficient historical data on malaria distribution and activity to determine the role of warming, if any, in the recent resurgence of malaria in the highlands of Kenya, Uganda, Tanzania, and Ethiopia (Cox *et al.*, 1999).

That malaria is sensitive to temperature in some highland regions is illustrated by the effect of El Niño. Increases in malaria have been attributed to observed El Niño-associated warming in highland regions in Rwanda (Loevinsohn, 1994) and Pakistan (Bouma *et al.*, 1996). However, increases in rainfall (sometimes associated with El Niño) also trigger highland epidemics (e.g., Uganda—Lindblade *et al.,* 1999). Lindsay *et al.* (2000) found a reduction in malaria infection in Tanzania associated with El Niño when heavy rainfall may have flushed out Anopheline mosquitoes from their breeding sites.

Most increases in malaria transmission entail single epidemics or a sequence of epidemics that occur over a 1- to 2-year period. Although many epidemics are triggered by transient increases in temperature and/or rainfall, the short time scale of events and the difficulty of linking different epidemics in different parts of the world make it difficult to say if long-term climate change is a factor. Furthermore, there has been little work that identifies where malaria transmission currently is limited by temperature and therefore where highland populations are at risk of malaria as a result of climate change. To determine the role of climate in the increase in highland malaria, a comprehensive research effort is required, together with implementation of a sustainable disease surveillance system that combines trend analyses across multiple sites to account for substantial local factors.

number of new cases of a disease that will arise from one current case when introduced into a nonimmune host population during a single transmission cycle (Anderson and May, 1992). The basic reproduction rate—or a related concept, "vectorial capacity"—can provide a relative index of the impact of different climate scenarios on the transmissibility of vector-borne diseases such as malaria. Vectorial capacity, however, is determined by complex interactions of many host, vector, pathogen, and environmental factors. Some of the variables are sensitive to temperature, including mosquito density, feeding frequency, mosquito survival, and the extrinsic incubation period (EIP) of the parasite (plasmodium) in the mosquito (Martens *et al.*, 1999). The EIP is especially important, and, within the lower temperature range, it is very temperature-sensitive.

Biological (or process-based) models have been used to estimate the potential transmission of malaria. This is a measure of the extent to which the natural world (the global environment-climate complex) would allow the transmission of malaria if there were no other human-imposed constraints on transmission. However, in some areas where human-imposed constraints have occurred as a result of economic growth, or were put in place purposely, malaria transmission has been successfully controlled, regardless of suitable local temperatures. There has been considerable evolution of models since the SAR (Martens *et al.*, 1995, 1997, 1999; Martin and Lefebvre, 1995). One model (Martens *et al.*, 1999) includes vector-specific information regarding the temperature-transmission relationship and mosquito distribution limits. Recent studies using that revised model applied to the HadCM2 climate scenarios project a global increase of 260–320 million people in 2080 living in the potential transmission zone (against a baseline expectation of about 8 billion—that is, a 2–4% increase in the number of people at risk) (Martens *et al.*, 1999; McMichael *et al.*, 2000a). This projection, by design, does not take into account the fact that much of this additional population at risk is in middle- or high-income countries where human-imposed constraints on transmission are greatest and where potential transmission therefore is unlikely to become actual transmission. The model also projects regional increases and a few decreases in the seasonal duration of transmission in current and prospective areas of malaria transmission. Constraining of GHG emissions to achieve CO_2 stabilization within the range 550–750 ppm would reduce those projected increases by about one-third (Arnell *et al.*, 2001).

On a global scale, all biological models show net increases in the potential transmission zone of malaria and changes in seasonal transmission under various climate scenarios (Martens *et al.*, 1995, 1999; Martin and Lefebvre, 1995). Some local decreases in malaria transmission also are predicted to occur where declines in rainfall would limit mosquito survival. The outputs of these malaria models are very sensitive to assumptions about the minimum rainfall or humidity levels needed for malaria transmission.

Another global modeling study (Rogers and Randolph, 2000) used a statistical-empirical approach, in contrast to the aforementioned biological models. The outcome variable in this model is the number of people living in an *actual* transmission zone, as opposed to a *potential* transmission zone (as estimated by biological models). Using an IS92a (unmitigated) climate scenario, this study estimated no significant net change by 2080 in the portion of the world's population living in actual malaria transmission zones; modeled malaria transmission increased in some areas and decreased in others. This study made the assumption that the actual geographic distribution of malaria in today's world is a satisfactory approximation of its historical distribution prior to modern public health interventions. This assumption is likely to have biased the estimation of the underlying multivariate relationship between climatic variables and malaria occurrence because the sensitive climate-malaria relationship in the lower temperature range in temperate zones (especially Europe and the southern United States) would have been excluded from the empirically derived equation. Hence, the use of that derived equation to predict malaria risk in 2080 would have been relatively inert to marginal climatic changes at the fringes of the current geographic distribution.

Another type of modeling addresses changes in the distribution of mosquito vector species only. The CLIMEX model estimates changes in global and national (Australia) distribution of malaria vectors under a range of climate scenarios, based on the vectors' temperature and moisture requirements (Bryan *et al.*, 1996; Sutherst, 1998). The distribution of *Anopheles gambiae* complex is projected to undergo a net increase in distribution in southern Africa under three climate change scenarios (Hulme, 1996). However, these models do not address complex ecological interactions, such as competition between species.

None of these models have been adequately validated at global or regional levels. Modeling to date has not satisfactorily addressed regional vulnerability to malaria or changes in risk in highland regions (Lindsay and Martens, 1998). This is principally because it is difficult to obtain sufficiently detailed geographic distribution maps of mosquitoes and malaria occurrence over time. An important criticism of biological models is that undue emphasis is placed on temperature changes, without consideration to other ecological complexities—including those influenced by rainfall, humidity, and host exposure—that influence transmission dynamics. Furthermore, the equations within a global model may be inappropriate for particular local conditions, and there is a need for cross-validation of large-scale and small-scale studies (Root and Schneider, 1995). Some attempts to apply these integrated modeling techniques to smaller scale regional settings have attempted to take account of local/regional conditions (Lindsay and Martens, 1998). None of the modeling to date has incorporated the modulating effect of public health strategies and other social adaptive responses to current or future malaria risk (Sutherst *et al.*, 1998). Nevertheless, it remains a legitimate and important question to estimate, under scenarios of climate change, change in the extent to which the natural world (the global environment-climate complex) would allow transmission of malaria if there were no other human-imposed constraints on transmission.

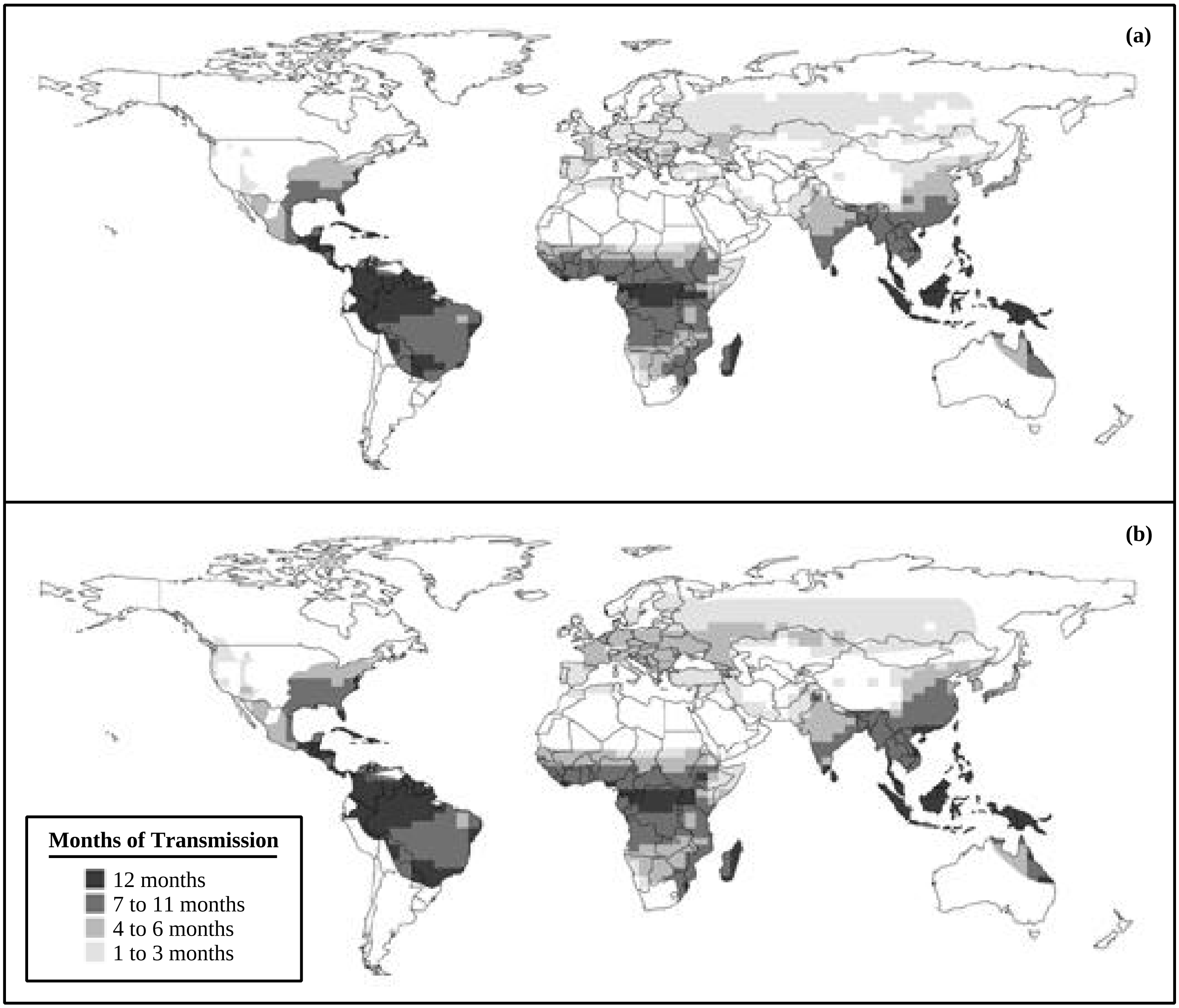

Figure 9-2: Potential impact of climate change on seasonal transmission of falciparum malaria. Output from MIASMA v2.0 malaria model (Martens *et al.*, 1999) indicates the number of months per year when climate conditions are suitable for falciparum transmission and where there is competent mosquito vector: (a) months of potential transmission under current climate (1961–1990); (b) months of potential transmission under a GHG-only climate scenario (HadCM2 ensemble mean) in the 2080s. Future changes in mosquito distributions are not modeled. This model does not take into account control or eradication activities that have significantly limited the distribution of malaria.

9.7.2. Dengue

Dengue is a disease that is caused by four closely related viruses that are maintained in a human-*Aedes aegypti*-human cycle in most urban centers of the tropics (Gubler, 1997). The geographic distribution of the dengue viruses and mosquito vectors (*Aedes aegypti* and *A albopictus*) has expanded to the point that dengue has become a major tropical urban health problem (Gubler, 1997, 1998b). Dengue is primarily an urban disease; more than half of the world's population lives in areas of risk (Gubler, 1997, 1998b). In tropical areas of the world, dengue transmission occurs year-round but has a seasonal peak in most countries during months with high rainfall and humidity. Major factors causing epidemics include population growth, rapid urbanization, lack of effective mosquito control, and movement of new dengue virus strains and serotypes between countries (Gubler, 1997, 1998b).

The global resurgence of dengue in recent years has resulted in increased imported dengue and cases of local transmission in the United States and Australia. As with malaria, the number of cases is small and sporadic (Gubler, 1989, 1997, 1998b). By contrast, Mexican states bordering the United States have had repeated large epidemics of dengue (Gubler, 1989, 1998b; Reiter, 1997; Rawlins *et al.*, 1998). The difference in vulnerability may be caused by differences in living standards and human behavior, which in the United States decrease the probability that vector mosquitoes will feed on humans. It is unlikely that climate change will affect these factors and cause increased epidemic dengue activity in temperate zone developed countries.

9.7.2.1 Modeling the Impact of Climate Change on Dengue

To date, all published studies regarding evaluations of the possible impact of global climate change on dengue transmission have involved modification of the standard equation for vectorial capacity (VC) (Jetten and Focks, 1997; Martens *et al.*, 1997; Patz *et al.*, 1998a). Temperature affects the rate of mosquito larval development, adult survival, vector size, and gonotrophic cycle, as well as the EIPof the virus in the vector (Focks *et al.*, 1993a,b, 1995).

Modeling studies (Jetten and Focks, 1997; Martens *et al*., 1997; Patz *et al*., 1998a) suggest that a warming projection of 2°C by 2100 will result in a net increase in the potential latitudinal and altitudinal range of dengue and an increase in duration of the transmission season in temperate locations. However, they also ignore the complex epidemiological and ecological factors that influence transmission of dynamics of dengue. Changes in potential transmission in areas that currently are endemic for dengue are projected to be limited. As with malaria, models indicate that the areas of largest change of potential transmission intensity as a result of temperature rise are places where mosquitoes already occur but where development of the virus is limited by temperature during part of the year. However, these models do not incorporate demographic, societal, and public health factors that have been responsible for eliminating dengue from temperate areas. Transmission intensity in tropical endemic countries is limited primarily by herd immunity, not temperature; therefore, projected temperature increases are not likely to affect transmission significantly. Moreover, in subtropical developed areas, where transmission is limited primarily by demographic and societal factors, it is unlikely that the anticipated temperature rise would affect endemicity (Gubler, 1998b).

9.7.3. Other Mosquito-Borne Viruses

Mosquitoes transmit many viruses, more than 100 of which are known to infect humans—causing illness ranging from acute viral syndrome to severe and sometimes fatal encephalitis and hemorrhagic fever. The natural transmission cycles of these viruses are complex and usually involve birds or rodents as well as several mosquito species; each region of the world has its own unique viruses (Gubler and Roehrig, 1998). These viruses have become important global emergent/resurgent public health problems in recent years, causing widespread epidemics (Gubler 1996, 1998a).

Yellow fever—a virus that occurs naturally in the rain forests of Africa and South America in an enzootic cycle involving lower primates and mosquitoes—also can cause major urban epidemics in a cycle involving *Aedes aegypti* that is identical to dengue (Monath, 1988). As such, it has similar weather and climate sensitivity to dengue. Yellow fever was effectively controlled in the 1950s and 1960s through vaccination (Africa) and mosquito control (the Americas). With reinvasion of most large American tropical urban centers by *Aedes aegypti* in the past 30 years (Gubler, 1989), the region is at its highest risk for urban epidemics in 50 years (Gubler, 1998c). Once urban epidemics of yellow fever begin to occur in tropical America, it is expected that this virus will move very quickly via modern transportation to Asia and the Pacific, where it has never occurred (Gubler, 1998c).

Several mosquito-borne viruses cause encephalitis, including eastern equine encephalitis (EEE), western equine encephalitis (WEE), St. Louis encephalitis (SLE), La Crosse encephalitis (LAC), and Venezuelan equine encephalitis (VEE) in the Americas; Japanese encephalitis (JE) in Asia; Murray Valley encephalitis (MVE) and Kuniin (KUN) in Australia; and West Nile (WN) and Rift Valley fever (RVF) viruses in Africa (Gubler and Roehrig 1998). WN virus also occurs in west and central Asia, the Middle East, and Europe and recently was introduced into the United States, where it caused a major epidemic in New York City (Asnis *et al.*, 2000; Komar, 2000). All of these viruses have birds (EEE, WEE, SLE, JE, MVE, KUN, WN) or rodents (LAC, VEE) as natural reservoir hosts. The natural host for RVF is not known, but large ungulates act as amplifying hosts.

Epidemics of these diseases occur when their natural ecology is disturbed in some way (Gubler and Roehrig, 1998). This could include environmental changes such as meteorological changes or forest clearing, changes in population densities and structure of the mosquito or vertebrate host, or genetic changes in the viruses. All of these diseases are very climate-sensitive, but it is difficult to know how climate change will influence their distribution and incidence because of the complexities of their transmission cycles in nature. For example, in the United States, WEE and SLE could expand their geographic distribution northward, and WEE could disappear from most of the country (Reeves *et al.*, 1994). Climate change also may have an effect on endemic/enzootic arboviruses in Australia (Russell, 1998; Tong *et al.*, 1998; Bi *et al.*, 2000). Thus, there probably would be positive and negative impacts, depending on the disease.

Floods may cause an immediate decrease in mosquito populations because of loss of breeding sites. However, disease risk may rise as floodwaters recede and vector populations increase, but only if the virus is present (Nasci and Moore, 1998). This underscores the need to have effective surveillance systems and prevention strategies in place to monitor disease and control vector activity, as well as the need for more research on the transmission dynamics of vector-borne diseases.

9.7.4. Leishmaniasis

There are two principal clinical types of leishmaniasis—visceral and cutaneous—which is caused by a range of species of *Leishmania* parasites. The parasites are transmitted by sandflies,

***Table 9-3**: Temperature thresholds of pathogens and vectors. T_{min} is minimum temperature required for disease transmission. T_{max} for the pathogen is upper threshold beyond which temperatures are lethal. T_{max} for vectors are not provided. Temperatures are in degrees Celsius. Note that temperatures assume optimum humidity; vector survival decreases rapidly as dryness increases. There is considerable variation in these thresholds within and between species (Purnell, 1966; Pfluger, 1980; Curto de Casas and Carcavallo, 1984; Molineaux, 1988; Rueda et al., 1990).*

Disease	Pathogen	T_{min}	T_{max}	Vector	T_{min} for Vector
Malaria	*Plasmodium falciparum*	16–19	33–39	*Anopheles*	8–10 (biological activity)
Malaria	*Plasmodium vivax*	14.5–15	33–39	*Anopheles*	8–10 (biological activity)
Chagas'disease	*Trypanosoma cruzi*	18	38	*Triatomine* bugs	2–6 (survival) 20 (biological activity)
Schistosomiasis	Cercaria	14.2	>37	Snails (*Bulinus* and others)	5 (biological activity) 25±2 (optimum range)
Dengue fever	Dengue virus	11.9	not known	*Aedes*	6–10
Lyme disease	*Borrelia burdorferi*	Not yet determined		*Ixodes* ticks	5–8

of which the two most important genera are *Phlebotomus* in Europe and Asia and *Lutzomyia* in the Americas. In central Asia and Europe, leishmaniasis has become an important co-infection with human imunodeficiency virus (HIV) (Alvar *et al.*, 1997; WHO/UNAIDS, 1998). Sandflies are very sensitive to temperature, and increases in temperature also may increase daily mortality rates. *Phlebotominae* are sensitive to sudden temperature changes and prefer regions with small differences between maximum and minimum temperatures. Thomson *et al.* (1999) mapped *P. orientalis* in Sudan and found that the geographic distribution was best explained by mean annual maximum daily temperature and soil type. One study on leishmaniasis in Italy indicates that climate change may expand the range of one vector (*P. perniciosus)* but decrease the range of another (*P. perfiliewi*) (Kuhn, 1997). A3°C increase in temperature could increase the geographic and seasonal distribution of *P. papatasi* in southwest Asia, provided other ecological requirements are met (Cross and Hyams, 1996; Cross *et al.*, 1996).

The southern limit of leishmaniasis and vectors in South America is the extreme north of Argentina (Curto de Cassas and Carcavallo, 1995; Marcondes *et al.*, 1997). There have been no systematic studies of the relationship between climate parameters and vectors or human cases in the Americas. Climate change could affect the geographical distribution of these vector species in Brazil, Paraguay, Bolivia, and Argentina (Carcavallo and Curto de Casas, 1996).

9.7.5. Schistosomiasis

Schistosomiasis, which is caused by five species of the trematode (flat worm) *Schistosoma*, requires water snails as an intermediate host. Worldwide prevalence has risen since the 1950s largely as a result of expansion of irrigation systems in hot climates where viable snail populations can survive and the parasite can find human parasite carriers (Hunter *et al.*, 1993). All three genera of snail hosts (*Bulinus*, *Biomphalaria,* and *Oncomelania*) can tolerate a wide temperature range. At low temperatures, snails are effectively dormant and fecundity is virtually zero, but survival is good. At high temperatures, births (egg production) increase, but so does mortality (Table 9-3). However, snails are mobile and can move to avoid extreme temperatures within their habitats; water can act as an efficient insulator (Hairston, 1973; Gillett, 1974; Schiff *et al.*, 1979). The precise conditions within water bodies that determine transmission depend on a host of environmental factors, including local geology and topography, the general hydrology of the region, the presence or absence of aquatic vegetation, and local agricultural usage (Appleton and Stiles, 1976; Appleton, 1977). In east Africa, colonies of *Biomphalaria* and *Bulinus spp*. persist at altitudes of 2,000 m or more, but transmission—if it occurs at all—is restricted to brief warm seasons. Climate change might allow schistosomiasis transmission to extend its range to higher altitudes. Conversely, increasing temperatures at sea level could decrease transmission unless the snails move to cooler refuges.

Water shortages resulting from climate change could create greater need for irrigation, particularly in arid regions. If irrigation systems expand to meet this need, host snail populations may increase (Schorr *et al.*, 1984), leading to greater risk of human infection with the parasite. However, this impact could be reduced by constructing irrigation systems that are not conducive to snail breeding.

9.7.6. Chagas'Disease

The geographical distribution of American trypanosomiasis (Chagas' disease) is limited to the Americas, ranging from the southern United States to southern Argentina and Chile (Carcavallo *et al.*, 1998, 1999). Chagas'disease is transmitted by triatomine bugs (see Table 9-3). Temperature affects the major components of VC (reviewed by Zeledón and Rabinovich, 1981; Carcavallo, 1999). If temperatures exceed 30°C and humidity does not increase sufficiently, the bugs increase their feeding rate to avoid dehydration. If indoor temperatures rise, vector species in the domestic environment may develop shorter life cycles and higher population densities (Carcavallo and Curto de Casas, 1996). High temperatures also accelerate development of the pathogen, *Trypanosoma cruzi*, in the vector (Asin and Catalá, 1995). Many vector species are domesticated. Lazzari *et al.* (1998) found that in the majority of structures, differences between inside and outside temperature were small, although differences in humidity were significant. Triatomine dispersal also is sensitive to temperature (Schofield *et al.*, 1992). Population density of domestic vectors also is significantly affected by human activities to control or eradicate the disease (e.g., replastering of walls, insecticide spraying). The southern limits of *Triatoma infestans* and Chagas' disease distributions recently have been moved significantly inside their climatically suitable limits by large-scale control campaigns (Schofield and Dias, 1999).

9.7.7. Plague

Plague is a bacterial disease that is transmitted by the bite of infected fleas (*Xenopsylla cheopis*), by inhaling infective bacteria, and, less often, by direct contact with infected animals (Gage, 1998). Plague exists focally in all regions except Europe. Notable plague outbreaks have occurred in several Asian, African, and South American countries in the past 10 years (John, 1996; WHO, 1997; Gage, 1998; PAHO, 1998). It is unclear whether climate change may affect the distribution and incidence of plague. There does appear to be a correlation between rainfall patterns and rodent populations (Parmenter *et al.*, 1999; see also Section 9.7.9). Prospective field research studies must be conducted to confirm this.

9.7.8. Tick-Borne Diseases

Tick-borne diseases—in particular, Lyme disease, Rocky Mountain spotted fever, ehrlichiosis, and tick-borne encephalitis (TBE)—are the most common vector-borne diseases in temperate zones in the northern hemisphere. Ticks are ectoparasites; their geographical distribution depends on the distribution of suitable host species—usually mammals or birds (Glass *et al.*, 1994; Wilson, 1998). Species that transmit these diseases have complex life cycles that require 3 years and three different hosts species—one for each stage of the cycle (larvae, nymph, and adult). Climate directly and indirectly influences the tick vector, its habitat, host and reservoir animals, time between blood meals, and pathogen transmission. Bioclimatic threshold temperatures set limits for tick distribution and are of importance for the magnitude of disease occurrence (Table 9-3). Temperatures must be sufficiently high for completion of the tick's life cycle. Humidity must be sufficient to prevent tick eggs from drying out. Temperatures above the optimum range reduce the survival rate of ticks. In temperate countries, tick vectors are active in the spring, summer, and early autumn months.

Over the past 2 decades, marked increases have been reported in the abundance of ticks and the incidence of tick-borne disease in North America and Europe. In North America, these changes have been attributed to an increase in awareness of tick-borne diseases and increased abundance of wild tick hosts (principally deer), as reforestation has expanded areas of suitable habitat (Dennis, 1998). There is some evidence that the northern limit of distribution of the tick vector (*Ixodes ricinus*) and tick density increased in Sweden between the early 1980s and 1994, concurrent with an increased frequency of milder winters (Talleklint and Jaenson, 1998; Lindgren *et al.*, 2000). In New York state, *Ixodes scapularis* has expanded its geographic distribution northward and westward in the past 10 years. The reasons for this expansion are unknown.

9.7.8.1. Lyme Disease

Lyme disease is caused by infection with the spirochete *Borrelia burgdorferi*. It is transmitted by ticks of the *Ixodes ricinus* complex (Dennis, 1998). Lyme disease has a global distribution in temperate countries of North America, Europe, and Asia. The transmission cycle of Lyme disease involves a range of mammalian and avian species, as well as tick species—all of which are affected by local ecology. Under climate change, a shift toward milder winter temperatures may enable expansion of the range of Lyme disease into higher latitudes and altitudes, but only if all of the vertebrate host species required by the tick vector also are able to expand their distribution. A combination of milder winters and extended spring and autumn seasons would be expected to prolong seasons for tick activity and enhance endemicity, but this would not be expected to change disease activity because humans usually are infected by the nymphal stage, which feeds at a specific time during the second year of the cycle.

9.7.8.2. Tick-Borne Encephalitis

Tick-borne encephalitis (TBE) is caused by two closely related but biologically distinct viruses (Gubler and Roehrig, 1998). The eastern subtype is transmitted by *Ixodes persulcatus* and causes Russian spring-summer encephalitis. It occurs from China to eastern Europe and is highly focal in its distribution. The western subtype is transmitted by *Ixodes ricinus* and causes central European encephalitis, a milder form of the disease. It occurs within discrete foci from Scandinavia in the north to Croatia in the south, with only occasional cases further south. A related virus, Powassan, occurs in Canada and the United States and is transmitted by *Ixodes scapularis*. Humans usually become infected when they are exposed to ticks in habitats where the viruses are maintained. The viruses also may be transmitted directly through ingestion of raw goat milk.

It is possible that warming would extend the transmission season for TBE in Europe. The aforementioned study showed a northward extension of the tick population in Sweden in association with warmer winters, accompanied by an increase in the annual number of cases of tick-borne encephalitis reported within Sweden. Most transmission to humans is by the nymphal ticks, each of which feeds for a few days during spring-summer before dropping to the ground and molting to adult ticks, which feed primarily on deer and other large mammals. All tick stages have well-defined seasons of feeding activity, which vary geographically and may be prolonged in regions with mild winters.

Unlike Lyme disease, sustainable transmission of TBE requires a high level of coincident feeding of larval and nymphal ticks. This seasonal synchrony depends on a particular seasonal profile of land surface temperature—specifically, a rapid rate of cooling in the autumn (Randolph *et al.*, 2000). Synchrony may be disrupted by climate change as patterns of overwinter development by ticks are changed. A statistical model, based on the current distribution of TBE, indicates significant net contraction in the geographic distribution of TBE under mid-range climate scenarios by the 2050s (Randolph and Rogers, 2000). The model indicates that although disease foci spread to higher latitudes and altitudes, current foci in central Europe largely disappear as a result of disruption of the tick seasonal dynamic by climate change. Thus, one model suggests that it is unlikely that warming would increase the incidence or net geographic distribution of TBE in Europe.

9.7.9. Rodent-Borne Diseases

Rodent-borne diseases are zoonoses that are transmitted directly to humans by contact with rodent urine, feces, or other body fluids (Mills and Childs, 1998; Peters, 1998). Rodents are principle hosts for arthropod vectors such as fleas (see Section 9.7.7) and ticks (see Section 9.7.8). Environmental factors that affect rodent population dynamics include unusually high rainfall, drought, and successful introduction of exotic plant species. Rodent-borne pathogens are affected indirectly by ecological determinants of food sources that affect rodent population size (Williams *et al.*, 1997; Engelthaler *et al.*, 1999).

9.7.9.1. Leptospirosis

Leptospirosis is an acute febrile disease caused by the bacteria *Leptospira*. It probably is the most widespread zoonotic disease in the world and is particularly common in the tropics (PAHO, 1998). Infection is caused by exposure to water, damp soil, or vegetation contaminated with the urine of infected wild and domestic animals (e.g., rodents and dogs) (Thiermann, 1980). Outbreaks often occur after heavy rainfall and during floods (Kriz *et al.*, 1998; Trevejo *et al.*, 1998). Therefore, any increase in flooding associated with climate change may affect the incidence of this disease.

9.7.9.2. Hantaviruses

Several hantaviruses are capable of causing severe, often fatal, illness in humans (PAHO, 1998). Each has a specific geographic distribution that is determined by that of the primary rodent host (Schmaljohn and Hjelle, 1997). Humans are infected by aerosol exposure to infectious excreta or occasionally by bites. The better known of these diseases are hemorrhagic fever with renal syndrome, caused by Hantaan virus, in China and Korea and hantavirus pulmonary syndrome in the Americas, caused by several viruses that are specific to their rodent host (Schmaljohn and Hjelle, 1997). Outbreaks of disease may be associated with weather that promotes rapid increases in rodent populations, which may vary greatly between seasons and from year to year (Glass *et al.*, 2000). Many hantavirus infections occur in persons of lower socioeconomic status, where poorer housing and agricultural activities favor closer contact between humans and rodents (Schmaljohn and Hjelle, 1997). Arenaviruses (Lassa, Junin, Machupo, etc.), which are ecologically similar to hantaviruses, may respond similarly (Mills and Childs, 1998).

9.7.10. Water-Related Infectious Diseases

There are complex relationships between human health and problems of water quality, availability, sanitation, and hygiene. Predicting the potential impacts of climate change on water-related diseases therefore is difficult because access to a clean safe water supply is determined primarily by socioeconomic factors. Extreme weather—floods or droughts—can increase the risk of disease via contamination of water resources, poor hygiene, or other mechanisms. Currently, the World Health Organization (WHO) estimates that more than 1 billion people worldwide are without access to safe drinking water and that every year as many as 4 million die prematurely because they do not have access to safe drinking water and sanitation. Increases in water stress are projected under climate change in certain countries (see Chapter 4), but it is difficult to translate such indicators directly into the attributable risk for water-related diseases. Water scarcity may necessitate use of poorer quality sources of freshwater, such as rivers, which often are contaminated. Decreases in water supplies could reduce the water available for drinking and washing and lower the efficiency of local sewerage systems, leading to increased concentration of pathogenic organisms in raw water supplies.

Excessive precipitation can transport terrestrial microbiological agents into drinking-water sources. For example, some outbreaks of cryptosporidiosis, giardia, and other infections have been triggered by heavy rainfall events in the UK and United States (Lisle and Rose, 1995; Atherholt *et al.*, 1998; Rose *et al.*, 2000; Curriero *et al.*, 2001). Significant correlation between the cumulative monthly distribution of cholera cases and the monthly distribution of precipitation has been observed in Guam (Borroto and Haddock, 1998). In many countries, handling of sewage is not separate from the drainage system for stormwaters. It is important that water resource management can adapt to changes in the frequency of precipitation extremes to minimize the risk of microbiological contamination of the public water supply.

Cholera is a water- and food-borne disease and has a complex mode of transmission. In tropical areas, cases are reported year-round. In temperate areas, cases are reported mainly in the warmest season. The seventh cholera pandemic currently is spreading across Asia, Africa, and South America. A new serogroup (*V. cholerae* O139) appeared in 1992 and is responsible for large epidemics in Asia. During the 1997–1998 El Niño, excessive flooding caused cholera epidemics in Djibouti, Somalia, Kenya, Tanzania, and Mozambique (WHO, 1998b). Birmingham *et al.* (1997) found a significant association between bathing and drinking water from Lake Tanganyika and the risk of infection with cholera. Warming in the African Great Lakes may cause conditions that increase the risk of cholera transmission in the surrounding countries (WHO, 1998b). See Section 9.8 for a discussion of cholera in coastal waters.

9.7.11. Other Infectious Diseases

Water- and food-borne diseases tend to show marked seasonality, with peaks in early spring or summer. Higher temperatures favor microorganism proliferation and often are associated with an increase in gastrointestinal infections. Above-average temperatures in Peru during the 1997–1998 El Niño were associated with a doubling in the number of children admitted to the hospital with diarrhea (Checkley *et al.*, 2000). Higher temperatures also can trigger spore maturation (e.g., *Cyclospora cayetanensis*—Ortega *et al.*, 1993; Smith *et al.*, 1997). In Peru, the incidence of cyclosporosis peaks in the summer months (Madico *et al.*, 1997). Because climate change is expected to entail warmer springs and summers, additional cases of food-borne disease may occur, if current trends continue (Bentham and Langford, 1995). In most developed countries, food-borne disease incidence is increasing as a result of changes in behavior, consumption patterns, and commerce.

Major epidemics of meningococcal infection usually occur every 5–10 years within the African "meningitis belt;" they usually start in the middle of the dry season and end a few months later with the onset of the rains (Greenwood *et al.*, 1984). Between February and April 1996, the disease affected thousands of people in parts of northern Nigeria, many of whom died (Angyo and Okpeh, 1997). The epidemic spread from the original meningitis belt to Kenya, Uganda, Rwanda, Zambia, and Tanzania (Hart and Cuevas, 1997). One of the environmental factors that predispose to infection and epidemics is low humidity (Tikhoumirov *et al.*, 1997). However, a climate-meningitis association was not clear in parts of the Gulf of Guinea (Besancenot, 1997). The fact that this disease has been limited to semi-arid areas of Africa suggests that its transmission could be affected by warming and reduced precipitation.

Warm and humid conditions can promote fungal skin infections such as sporotrichosis (Conti Diaz, 1989). Decreases in humidity can lead to increased dispersion of particulate fungal spores, thereby increasing the risk of pneumonia caused by coccidioidomycosis (Durry *et al.*, 1997; Schneider *et al.*, 1997).

9.8. Coastal Water Issues

Pathogens often are found in coastal waters; transmission occurs though shellfish consumption or bathing. Coastal waters in developed and developing countries frequently are contaminated with untreated sewage. Higher temperatures encourage microorganism proliferation. The presence of *Vibrio spp*. (some of which are pathogens that cause diarrhea) has been associated with higher sea-surface temperature (SST) (Lipp and Rose, 1997). *Vibrio vulnificus* is a naturally occurring estuarine bacterium that may be more often transmitted to humans under conditions of higher SST (Patz *et al.*, 2000).

Acute poisoning can occur following consumption of fish and shellfish contaminated with biotoxins (WHO, 1984). Phytoplankton organisms respond rapidly to changes in environmental conditions and therefore are sensitive biological indicators of the combined influences of climate change and environmental change (Harvell *et al.*, 1999). Algal blooms are associated with several environmental factors, including sunlight, pH, ocean currents, winds, SSTs, and runoff (which affects nutrient levels) (Epstein *et al.*, 1993; NRC, 1999). Algal blooms can be harmful to fish and other aquatic life, often causing severe economic damage, and are reported to have increased globally in the past several decades (Hallegraeff, 1993; Sournia, 1995), although some of the observed increase is attributed to changes in monitoring, effluent, and land use.

There is no straightforward relationship between the presence of an algal bloom and an outbreak of poisoning. Human poisoning can occur in the absence of a bloom. Two main types of biotoxin poisoning are associated with temperate climates and colder coastal waters: paralytic shellfish poisoning and diarrheic shellfish poisoning. If water temperatures rise as a result of climate change, shifts in the distribution of these diseases could follow. Biotoxins associated with warmer waters, such as ciguatera in tropical waters, could extend their range to higher latitudes (Tester, 1994). An association has been found between ciguatera (fish poisoning) and SST in some Pacific islands (Hales *et al.*, 1999a).

Recent evidence suggests that species of copepod zooplankton provide a marine reservoir for the cholera pathogen and facilitate its long-term persistence in certain regions, such as the estuaries of the Ganges and Bramaputra in Bangladesh (Colwell, 1996). The seasonality of cholera epidemics may be linked to the seasonality of plankton (algal blooms) and the marine food chain. Studies using remote-sensing data have shown a correlation between cholera cases and SST in the Bay of Bengal (Lobitz *et al.*, 2000). Interannual variability in cholera incidence in Bangladesh also is linked to ENSO and regional temperature anomalies (Pascual *et al.*, 2000). Epidemiological evidence further suggests a widespread environmental cause of the 1991 epidemic in Peru, rather than point-source contamination (Seas *et al.*, 2001). There is some evidence for a link between warmer sea surfaces and cholera risk in the Bay of Bengal, but it is not possible to extrapolate such findings to cholera incidence inland or in other regions. The potential impact of long-term climate warming on cholera incidence or risk of epidemics remains uncertain.

Climate-related ecological changes may enhance primary and secondary transmission of cholera in developing countries, particularly among populations settled in low-lying coastal areas in the tropics. However, the causal link between sea temperature, plankton blooms, and human disease requires further elucidation and confirmation.

9.9. Food Yields and Nutrition

Background climate and annual weather patterns are key factors in agricultural productivity, despite technological advances such as improved crop varieties and irrigation systems. As temperature, rainfall, and soil moisture change, plant physiology is affected; so too is the much less predictable risk of a change in patterns of plant pests and pathogens. There are many social, economic, and environmental influences on agricultural, horticultural, and livestock productivity. Climate change represents an additional pressure on the world food supply system. That system, which has yielded an overall increase in per capita food supplies over the past 4 decades, has shown signs of faltering over the past decade. There is ongoing scientific debate about the relative importance of economic, technical, and ecological influences on current food yields (Waterlow *et al.*, 1998; Dyson, 1999). Optimists point to falling food prices; pessimists point to falling soil fertility.

Modeling studies (reviewed in Chapter 5) indicate that, under climate change, yields of cereal grains (the world's dominant food commodity) would increase at high and mid-latitudes but decrease at lower latitudes. Furthermore, this disparity would become more pronounced as time progresses. The world's food system may be able to accommodate such regional variations at the global level, with production levels, prices, and the risk of hunger relatively unaffected by the additional stress of climate change. To minimize possible adverse consequences, a dual development program is desirable. Adaptation should be undertaken via continued development of crop breeding and management programs for heat and drought conditions. These will be immediately useful in improving productivity in marginal environments today. Mitigation strategies should be implemented to try to reduce further enhanced global warming. However, recent work suggests that the main benefits of mitigation will not accrue until late in the 21st century (Parry *et al.*, 1998).

The United Nations Food and Agriculture Organization (FAO) estimates that in the late 1990s, 790 million people in developing countries did not have enough to eat (FAO, 1999). The FAO report on food insecurity has identified population groups, countries, and regions that are vulnerable. For example, nearly half the population in countries of central, southern, and east Africa are undernourished. Environmental factors, including natural factors and those that are a consequence of human activities, can limit agricultural potential. These factors include extremely dry or cold climates, poor soil, erratic rainfall, steep slopes, and severe land degradation. The FAO report further states that undernutrition and malnutrition prevail in regions where environmental, economic, and other factors expose populations to a high risk of impoverishment and food insecurity.

Undernutrition is a fundamental cause of stunted physical and intellectual development in children, low productivity in adults, and susceptibility to infectious disease in everyone. Decreases in food production and increases in food prices associated with climate change would increase the number of undernourished people. Conversely, if food production increases and food prices decrease, the number of undernourished people would fall, but populations in isolated areas with poor access to markets still may be vulnerable to locally important decreases or disruptions in food supply.

9.10. Demographic and Economic Disruption

Health impacts associated with population displacement fall under two general categories: health impacts resulting from the new ecological environment and health impacts resulting from the living environment in refugee camps (Prothero, 1994). Even displacement from longer term cumulative environmental deterioration is associated with such health impacts. Cumulative changes that may cause population displacement include land degradation, salinity, deforestation, waterlogging, desertification, and water scarcity. When pastoralists in west Africa were forced to move because of reduced pasture and water, they were faced with new ecological conditions. They experienced psychological stress and were more at risk of infectious diseases (Stock, 1976; Prothero, 1994). Climate change may affect human security via changes in water supplies and/or agricultural productivity (Lonergan, 1998, 1999). An increase in the magnitude and frequency of extreme events also would be disruptive to political stability.

Immediate environmental catastrophes can force sudden displacement of a population. In these cases, adverse health impacts usually result from living in refugee camps in overcrowded, poor accommodations with inadequate food, water supplies, sanitation, and waste disposal (Shears *et al*., 1985; Noji, 1997). These conditions predispose people to parasitic and communicable diseases such as malaria and cholera, respiratory infections, intestinal disorders, malnutrition, and psychological stress (Prothero, 1994).

The potential impacts of sea-level rise on the health and well-being of coastal populations are an important consideration (Klein and Nicholls, 1999). Estimates of the potential number of people at risk from sea-level rise are addressed elsewhere in TAR WGI and this volume. For example, a 0.5-m rise in sea level along the Nile delta would flood 32% of urban areas, resulting in a significant loss of shelter and forced migration (El-Raey *et al.*, 1999; see Chapter 6). In some locations, sea-level rise could disrupt stormwater drainage and sewage disposal and result in salinization of freshwater supplies. It can affect health indirectly by reducing food production—for example, by reducing rice production in low-lying coastal rice paddies. Sea-level rise also could affect the distribution of vector-borne diseases—for example, some of the coastal wetlands of the United States may be flooded, thereby destroying the habitat of the EEE virus. Populations with limited economic, technical, and social resources have increased vulnerability to various infectious, psychological, and other adverse health consequences.

9.11. Adaptation Options

Adaptation measures can be used effectively to greatly reduce many of the potential health impacts of climate change (Gubler, 1998d; McMichael and Kovats, 2000; WHO, 2000). The most important, cost-effective, and urgently needed measure is to rebuild public health infrastructure. In very many countries of the world, this infrastructure has declined in recent years. Many diseases and public health problems that otherwise may be exacerbated by climate change could be prevented substantially or completely with adequate financial and public health resources. These resources would encompass public health training programs, research to develop and implement more effective surveillance and emergency response systems, and sustainable prevention and control programs.

Understanding vulnerability to changes in ranges or rates of diseases is the first step in addressing adaptive capacity. Adaptation involves the ability to change behavior or health infrastructure to reduce these potential negative impacts or increase potential positive impacts of climate change. Interventions early in the causal chain of disease are preferred (e.g., "primary" prevention to remove or reduce risks before any human cases occur). To the extent that this is not always feasible (or the risk factors unknown), "secondary prevention" or surveillance for early warning to prevent any further cases also is important.

Adaptation is a function of several societal systems, including access to financial resources (for individuals and populations), technical knowledge, public health infrastructure, and the capacity of the health care system. Note that there is much similarity in the determinants of adaptive capacity and those of vulnerability (see Section 9.3). Adaptation can occur via two routes: autonomous adaptation, which is the natural or spontaneous response to climate change by affected individuals, and purposeful adaptation, which is composed of planned responses to projected climate change—typically by governmental or other institutional organizations (MacIver and Klein, 1999). Purposeful adaptation also can occur via deliberate modification of personal, family, and community lifestyles, particularly in response to public education programs. Anticipatory adaptations are planned responses that take place in advance of climate change.

Adaptation to the impacts of climate change may occur at the population, community, or personal level (see Table 9-4). The capacity to adapt to potential changes in the climate will depend on many factors, including improving the current level of public health infrastructure; ensuring active surveillance for important diseases; and continuing research to further our understanding of associations between weather, extreme events, and vector-borne diseases. In addition, continuing research into medical advances required for disease prevention, control, and treatment—such as vaccines, methods to deal with drug-resistant strains of infectious agent, and mosquito control—is needed. More generally, research is needed to identify adaptation needs, evaluate adaptation measures, assess their environmental and health implications, and set priorities for adaptation strategies. The following subsections outline adaptive measures that have been developed for two areas of climate change impacts on health.

9.11.1. Extreme Events and Natural Disasters

Major impacts on human health may occur via changes in the magnitude and frequency of extreme events (see Table 3-10 and TAR WGI Chapter 9). Following Hurricanes George and Mitch, a range of policies to reduce the impacts of such extreme events has been identified (PAHO, 1999):

- Undertaking vulnerability studies of existing water supply and sanitation systems and ensuring that new systems are built to reduce vulnerability
- Developing improved training programs and information systems for national programs and international cooperation on emergency management
- Developing and testing early warning systems that should be coordinated by a single national agency and involve vulnerable communities providing and evaluating mental health care, particularly for those who may be particularly vulnerable to the adverse psychosocial effects of disasters (e.g., children, the elderly, and the bereaved).

Adaptation strategies to reduce heat-related mortality in vulnerable cities around the world include weather-based early warning systems (WMO, 1997; Ortiz *et al.*, 1998). A different system must be developed for each city, based on that city's specific meteorology. Specific weather/health thresholds are determined and used to call health warnings or advisories. Many systems are based on synoptic methodology; specific "offensive" air masses are identified and forecasts are developed to determine if they will intrude into a city within the next 60 hours. Two systems are under construction for Rome, Italy, and Shanghai (WMO, 1997).

Institutional and cultural barriers to the use of seasonal forecast information remain. Decisionmakers should be educated or encouraged to use scientific information that may lead to reduction in losses from natural disasters (Pfaff *et al.*, 1999).

Table 9-4*: Options for adaptation to reduce health impacts of climate change.*

Health Outcome	Legislative	Technical	Educational-Advisory	Cultural and Behavioral
Thermal stress	– Building guidelines	– Housing, public buildings, urban planning to reduce heat island effects, air conditioning	– Early warning systems	– Clothing, siesta
Extreme weather events	– Planning laws – Building guidelines – Forced migration – Economic incentives for building	– Urban planning – Storm shelters	– Early warning systems	– Use of storm shelters
Air quality	– Emission controls – Traffic restrictions	– Improved public transport, catalytic converters, smokestacks	– Pollution warning	– Carpooling
Vector-borne diseases		– Vector control – Vaccination, impregnated bednets – Sustainable surveillance, prevention and control programs	– Health education	– Water storage practices
Water-borne diseases	– Watershed protection laws – Water quality regulation	– Genetic/molecular screening of pathogens – Improved water treatment (e.g., filters) – Improved sanitation (e.g., latrines)	– Boil water alerts	– Washing hands and other hygiene behavior – Use of pit latrines

9.11.2. Malaria Epidemics

Malaria prevention illustrates approaches to adaptation that also apply to other vector-borne disease threats. To reduce the increased risks of malaria, human populations must take adaptive measures to diminish the impacts. Although malaria epidemics can be triggered by changes in meteorological or socioeconomic conditions, many health services fail to monitor these variables because indicators of risk for epidemic-prone areas have not been determined (Najera *et al*., 1998). Malaria surveillance and epidemic preparedness may benefit from recently developed tools that predict the seasonality and risks of epidemics by using satellite or ground-based meteorological data (e.g., Hay *et al.*, 1998; Patz *et al.*, 1998b). New approaches to mapping the distribution of malaria vectors over large areas may facilitate species-specific vector control activities. It has been shown in western Kenya that the risk of malaria transmission in the highlands can be predicted with a simple rainfall- and temperature-dependent predictive model (Githeko *et al.*, 2000).

Epidemics are focal in nature and often may be controlled by limited application of safe and effective residual insecticides. Parasite resistance to antimalarials is a threat to malaria control programs; therefore, it is essential that drug sensitivity is reviewed regularly. At the personal level, insecticide-protected fabrics (e.g., bednets) have been shown to be effective against infective mosquito bites (Legeler, 1998).

9.12. Secondary Health Benefits of Mitigation Policies

Actions taken to reduce GHG emissions are very likely to benefit population health (Wang and Smith, 1999; WHO, 1999c; OECD, 2000; see also TAR WGIII Chapter 9). Fossil fuel combustion releases local hazardous air pollutants (especially particulates, ozone, nitrogen oxides, and sulfur dioxide) and GHGs. Hence, policies to reduce GHG emissions via reductions in vehicle exhausts or an increase in the efficiency of indoor household cookstoves would yield great benefits to health (see also TAR WGIII Section 9.2.8.4). Controlling road traffic also would benefit health through reductions in road traffic accidents—a leading cause of death worldwide (Murray and Lopez, 1996).

The benefits to health from mitigation are highly dependent on the technologies and sectors involved. A study by Wang and Smith (1999) indicates that a significant number of premature

Box 9-3. Understanding El Niño Can Help Adaptation to Climate Change: Seasonal Climate Forecasting

There is evidence of an association between El Niño and epidemics of vector-borne diseases such as malaria and dengue in some areas where El Niño affects the climate (Kovats *et al*., 1999). Malaria transmission in unstable areas is particularly sensitive to changes in climate conditions, such as warming or heavy rainfall (Akhtar and McMichael, 1996; Gupta, 1996; Najera *et al.*, 1998). In Venezuela and Colombia, malaria morbidity and mortality increases in the year following the onset of El Niño (Bouma and Dye, 1997; Bouma *et al.*, 1997b; Poveda *et al.*, 2000). ENSO also has been shown to affect dengue transmission in some Pacific islands (Hales *et al.*, 1999b), though not in Thailand (Hay *et al.*, 2000). However, in many of the studies that have found a relationship between El Niño and disease, the specific climate drivers or mechanisms have not been determined. There also are other climate oscillations that are less well studied. Furthermore, there are other important explanations of cyclic epidemics, such as changes in herd immunity (Hay *et al.*, 2000).

The ENSO phenomenon provides opportunities for early warning of extreme weather, which could improve epidemic preparedness in the future. Seasonal forecasting methods and information have the potential to be used to far greater effect by the health sector (IRI, 1999; Kovats *et al.*, 1999). In addition to these direct applications, attention to the impacts of interannual climate variability associated with the ENSO phenomenon would help countries develop the necessary capacity and preparedness to address longer term impacts associated with global climate change (Hales *et al.*, 2000). On the other hand, there are limitations to using ENSO interannual climate variability to assess potential impacts of long-term climate change.

deaths can be prevented via reductions in particulate emissions in the household sector (i.e., domestic fuel use) in China. The Working Group on Public Health and Fossil Fuel Combustion (1997) estimates that a worldwide reduction in outdoor exposure to particulate matter (PM10), under a Kyoto-level (but global) emissions mitigation scenario, would avert 700,000 premature deaths annually by 2020 compared to a business-as-usual scenario. This figure, however, can be regarded only as indicative, given the broad assumptions and many uncertainties that underlay the estimation. Large numbers of people lack access to clean energy. Renewable energy sources—particularly solar and wind—could help provide this much needed energy while minimizing GHG emissions and maximizing health gain (Haines and Kammen, 2000).

9.13 Research and Information Needs, including Monitoring

Research on the health impacts of global climate change should be conducted within an international network of scientists. Climatic-environmental changes will vary by geographic location, and local populations vary in their vulnerability to such changes. Therefore, the patterns of health gains and losses will be very context-dependent. This type of research requires maximum exchange of information and cross-fertilization of ideas and techniques among scientists, agencies, and institutes. In particular, forecasting the likely health outcomes of exposure to future climate-environmental scenarios requires development of predictive models that can integrate across disparate systems. This will require an interdisciplinary approach. There is an urgent need to focus research efforts more sharply. Particular tasks include:

- Epidemiological studies of ongoing climatic variability and trends in relation to health
- Development of mathematical models to forecast likely health outcomes in relation to projected climatic/ environmental changes, accounting for concurrent social and economic circumstances and their projected changes
- Development of monitoring methods and systems to detect early evidence of health-related changes and further inform epidemiological and predictive modeling studies.

Monitoring of the potential impacts of climate change on health is important for several reasons (Campbell-Lendrum *et al.*, 2000; Kovats and Martens, 2000):

- Early detection of the health impacts of climate change
- Improved analysis of relationships between climate and health
- Validation of predictive models
- Increased understanding of vulnerability
- Assessment of effectiveness of adaptation strategies.

Epidemiological data are necessary to inform policymakers about the magnitude of actual or potential impacts of climate change. Most current infection surveillance systems have been designed to detect particular causes, such as food-borne disease, and individual risk factors, such as overseas travel. Monitoring of climate change requires a more comprehensive approach to infection etiology, examining the possible influence of climate on the environmental sources of pathogens and on human behavior (WHO-ECEH, 1998a,b). Another challenge for climate study is the size of data sets required. Although trends in any one country will be a starting point, improved coordination of infection data across regions will be needed. Epidemiological data also would help to determine the requirements for and the effectiveness of preventive actions.

Bioindicators of health risk also need to be developed, to detect early or unanticipated health impacts of climate change and stratospheric ozone depletion. For example, mapping and monitoring of vector species could be strengthened to detect early changes in their distribution associated with climate change (Campbell-Lendrum *et al*., 2000). The effect of extreme weather events such as heat waves and floods need to be included in enhanced surveillance for assessment of future impacts.

Populations vary in their vulnerability to health impacts and in the resources available for adaptive responses (McMichael *et al.*, 2000b). These differences in vulnerability, between and within populations, reflect a wide range of demographic, cultural, political, socioeconomic, and technological circumstances. In the future, national impact assessments should describe and identify means by which the vulnerability of populations and subgroups could be reduced and select priorities for monitoring.

9.14. Cross-Cutting Issues

9.14.1 Costing the Health Impacts of Climate Change

Costing the health impacts of climate change is complex and controversial. It is complex because of the great heterogeneity of the health impacts, which include death, infectious disease, nutritional deprivation, and post-traumatic stress disorders. It is controversial because of difficulties in assigning money values to a diverse range of health deficits, doing so across varied cultures and economies, and taking account of the full "stream" of health impacts into the future (with appropriate time-discounting). During the 1990s, an attempt was made to develop a more standardized approach to measurement of the population health deficit by combining chronic illness or disability and premature death, via weighting procedures, into an integrated index—the Disability-Adjusted Life Year (Murray, 1994; Murray and Lopez, 1996).

To date, however, there is negligible scientific literature on the population burden of disease attributable to current or future climate change. There is no such literature on the DALY-based impact. Hence, there is no basis for making overall estimates of the direct costs to society of the health impacts of climate change. Nevertheless, some approximate estimations have been published of the impacts on national economies of major infectious disease outbreaks, such as might occur more often under conditions of climate change. For example, the outbreak of plague-like disease in Surat, northwest India, in 1994 cost an estimated US$3 billion in lost revenues to India alone (John, 1996; WHO, 1997). The cost of the 1994 Dengue Haemorrhagic Fever (DHF) epidemic in Thailand was estimated to be US$19–51 million (Sornmani, *et al*., 1995). The cost of the 1994 epidemic of dengue/DHF in Puerto Rico was estimated to be US$12 million for direct hospitalization costs alone (Rodriguez, 1997; Meltzer *et al*., 1998).

9.14.2 Development, Sustainability, and Equity

The ideas of development, sustainability, and equity inform much of the content of this chapter. It has been noted repeatedly that health impacts will tend to occur unevenly in the world and that the impacts in poorer populations, especially in the least-developed countries, often will be augmented by the heightened vulnerability of those populations. That is one of several reasons why—in today's world in which the gap between rich and poor is widening (UNDP1999), in association with the nonredistributive character of market-dominated global economics (McMichael and Beaglehole, 2000)—new ways of redressing the imbalance in wealth and knowledge should be found.

The chapter also notes that development on a broad front—social, economic, technological, and provision of public health services and capacities—is crucial to a population's adaptive capacity to lessen the impacts of climate change.

Indeed, the health of a population is a key indicator of "sustainability." The capacity of the global population to achieve and maintain good health is an index of how well the natural and social environments are being managed. Wealthy local populations can afford to subsidize their health maintenance, drawing on resources imported from elsewhere. At a global level, however, health indicators provide a more valid indication of the extent to which the "carrying capacity" of the biosphere is being maintained.

9.15. Conclusions

The prospect of global climate change affecting patterns of human health poses a central challenge to scientists and policymakers. For scientists, the causation of most of the health outcomes considered in this chapter—from respiratory and cardiovascular disease to various types of infectious diseases—is complex: Various social, technological, demographic, behavioral, and environmental factors influence the risk of occurrence of these diseases. For that reason, it will remain difficult in the near future to identify any early impacts of the current climate trends on health. This complex causation of human disease also means that predictive modeling of future climatic impacts should take realistic account of the coexistent and modulating effects of nonclimate factors.

Over the past 5 years, we have acquired better understanding of direct temperature effects on health (heat and cold), temperature effects on air pollutant production, the seasonality of certain infectious diseases, and the public health consequences (and situational modifiers) of extreme weather events. Predictive modeling of how scenarios of future climate change would affect the patterns and impacts of vector-borne diseases has evolved, as has modeling of impacts on regional agricultural yields and the geography of world hunger.

Policymakers should appreciate that although our scientific capacity to foresee and model these various health outcomes of climate change continues to evolve, it is not possible to make precise and localized projections for many health outcomes—especially those that result indirectly from a sequence of impacts. In the meantime, a precautionary approach requires that policy development proceed on the basis of the available—though often limited and qualitative—evidence of how climate change will affect patterns of human population health. Furthermore, high priority should be assigned to improving the public health infrastructure and developing and implementing effective adaptation measures.

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